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The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

PART A

POWER ENGINEERING

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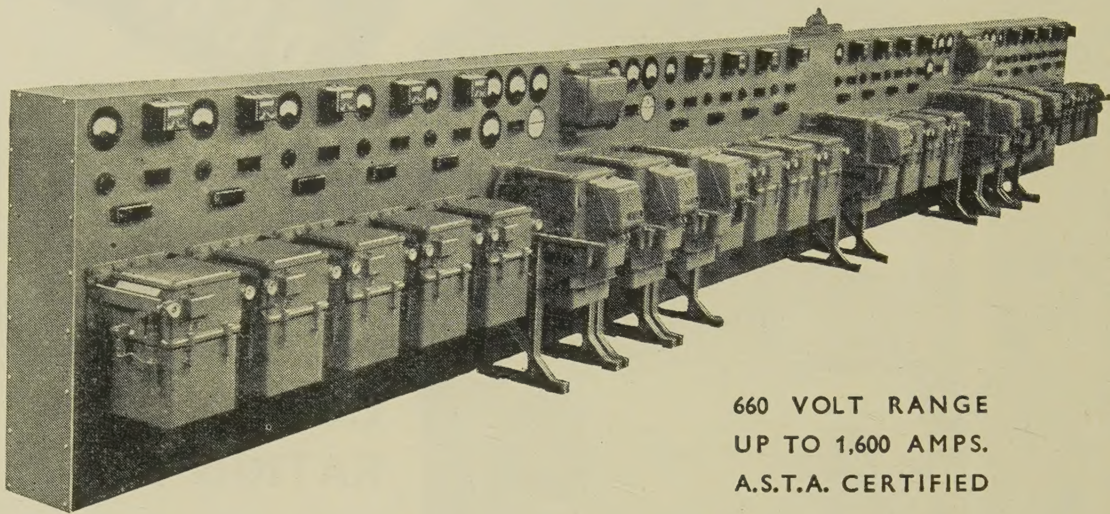

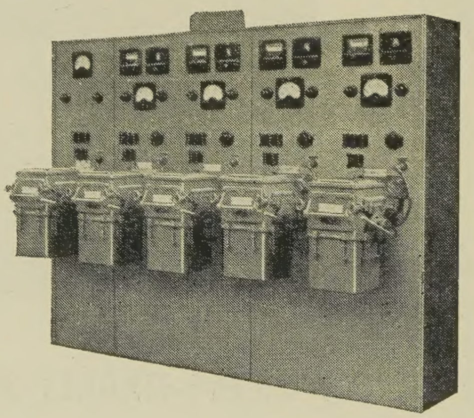

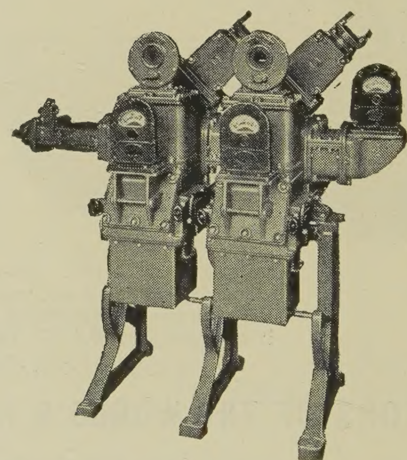

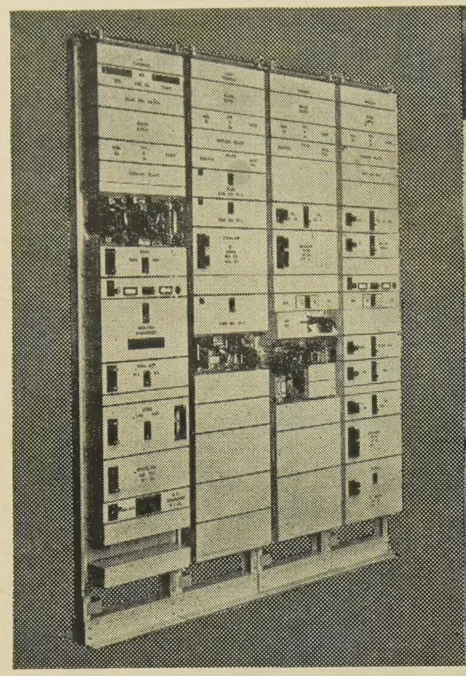

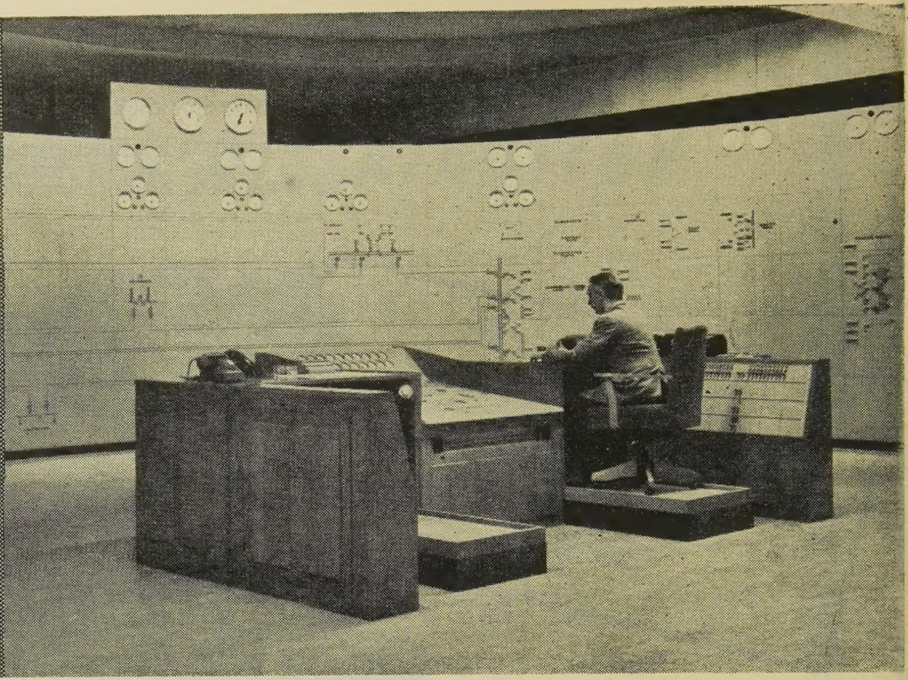

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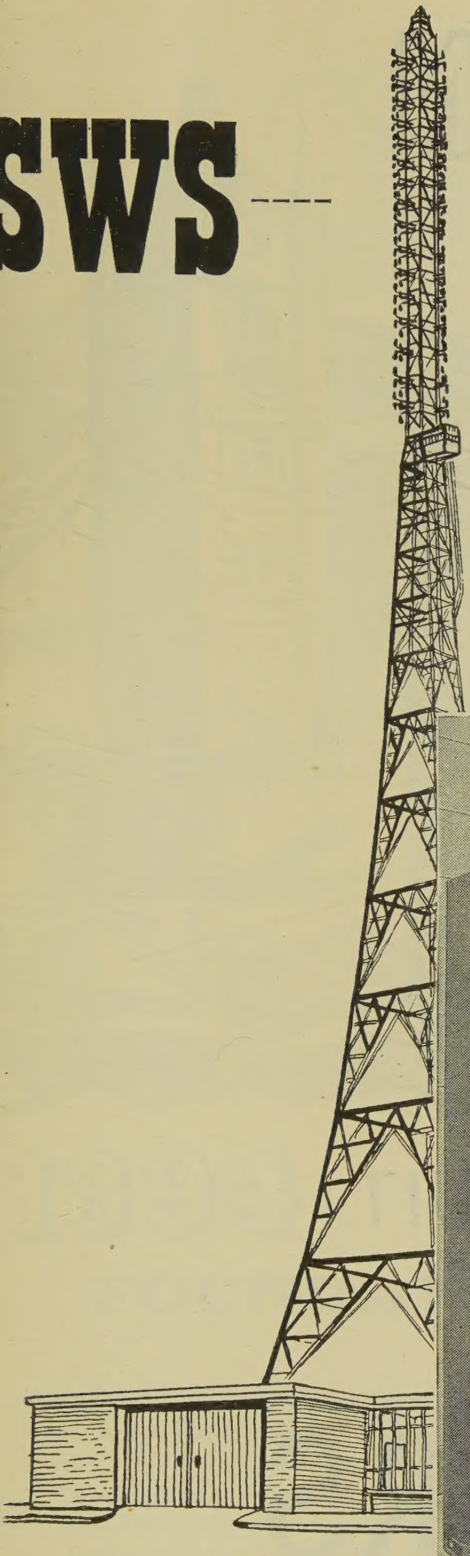

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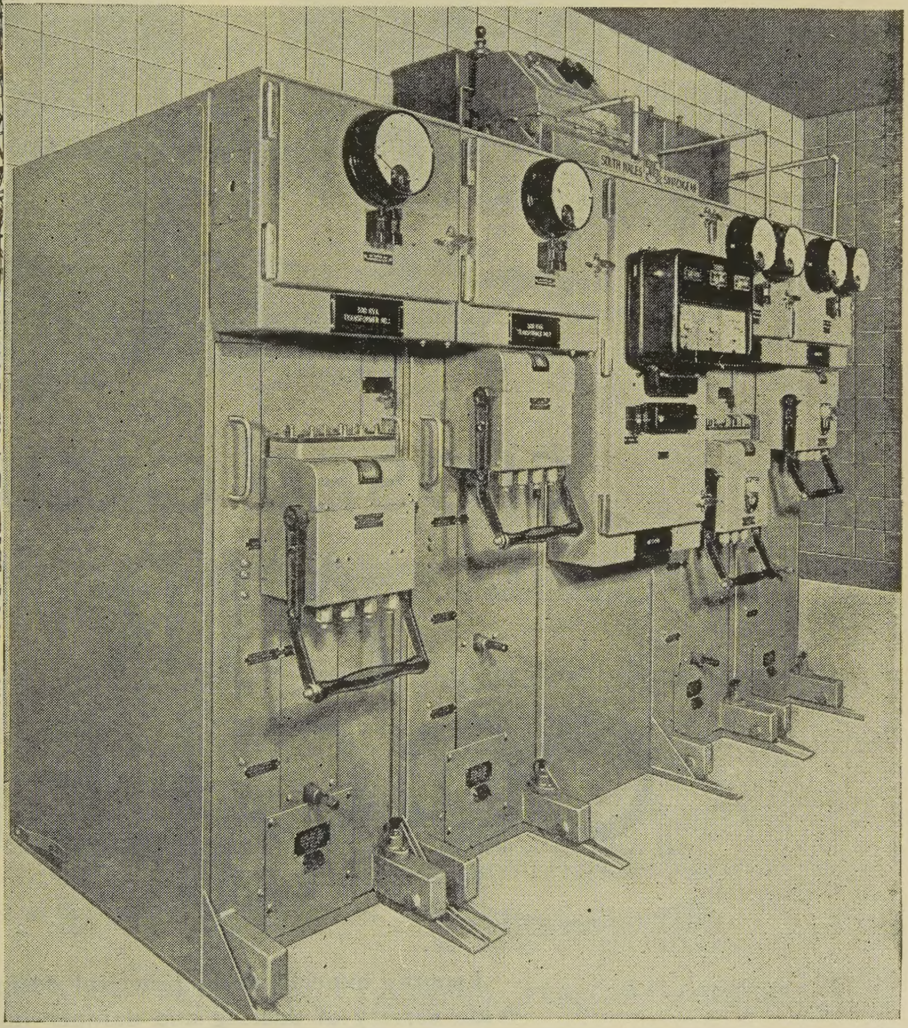

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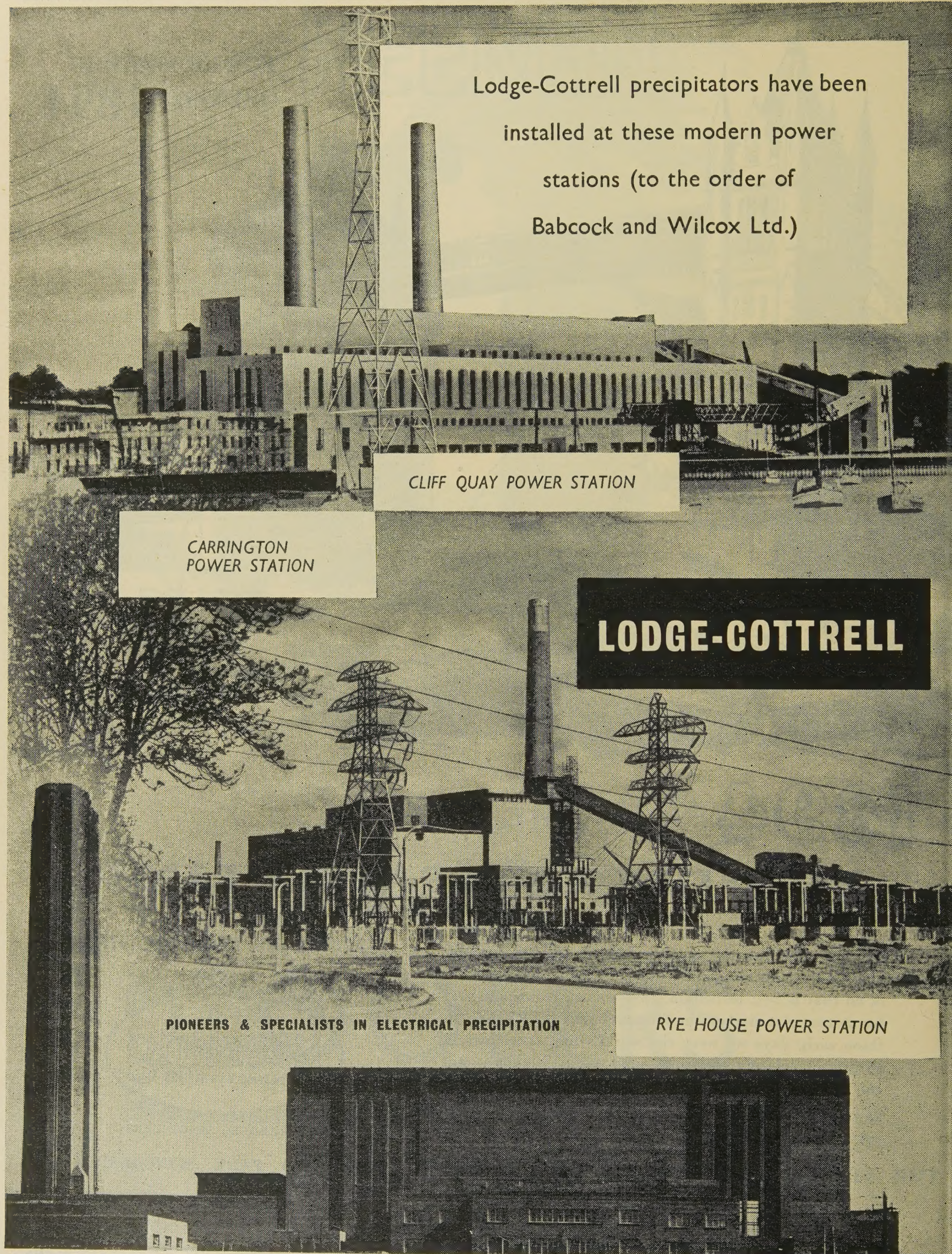

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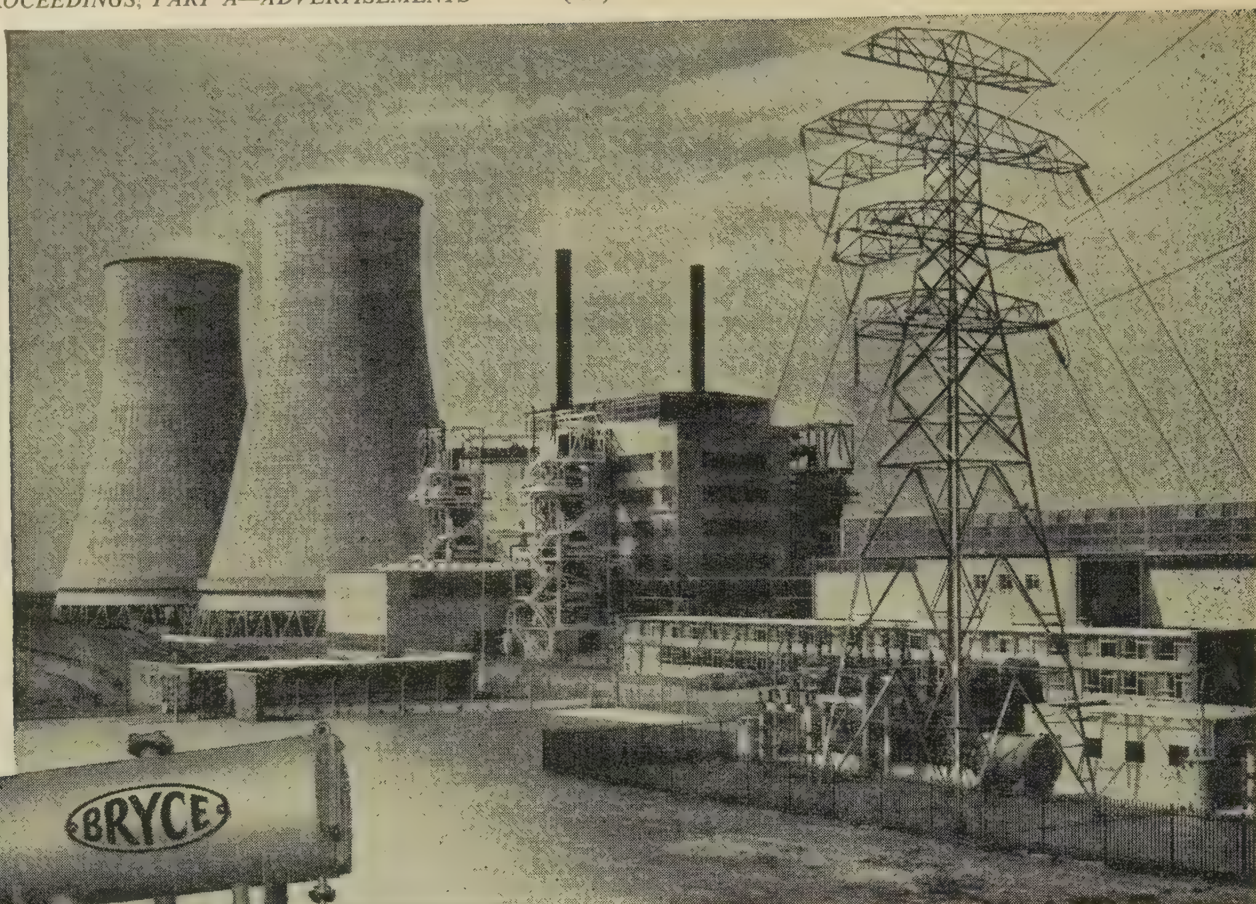

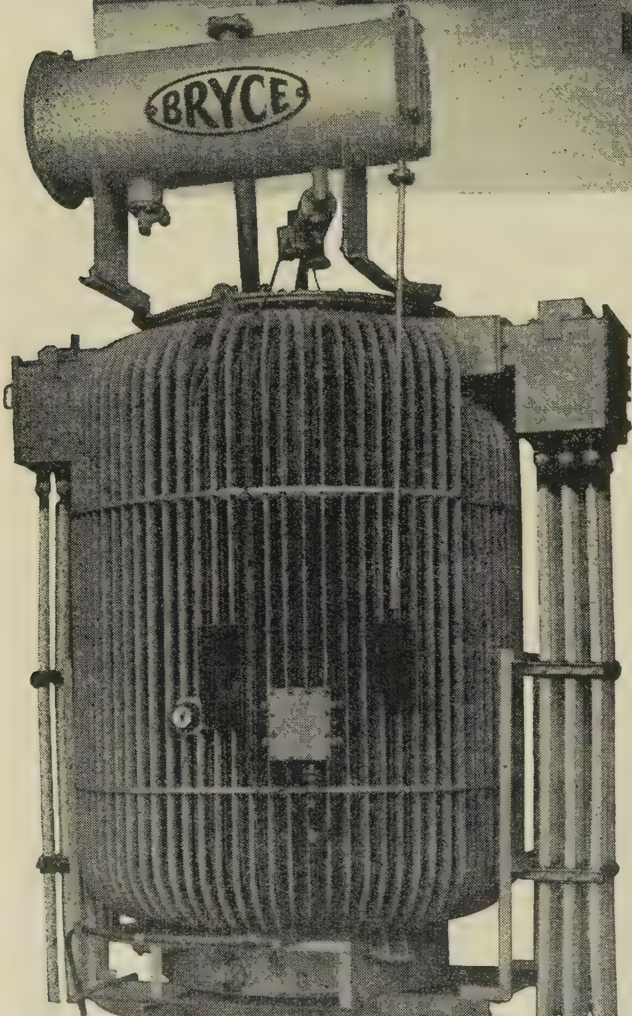

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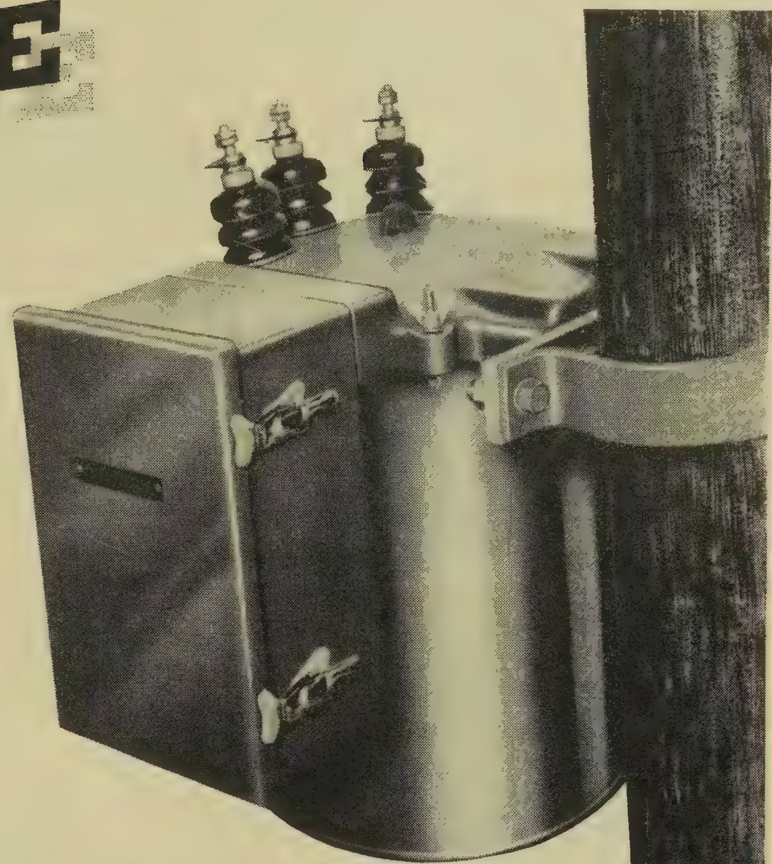

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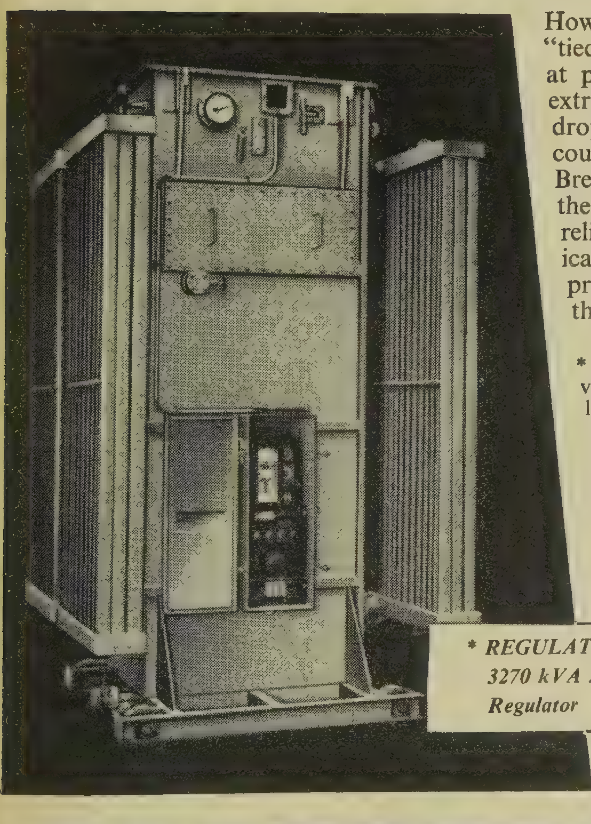

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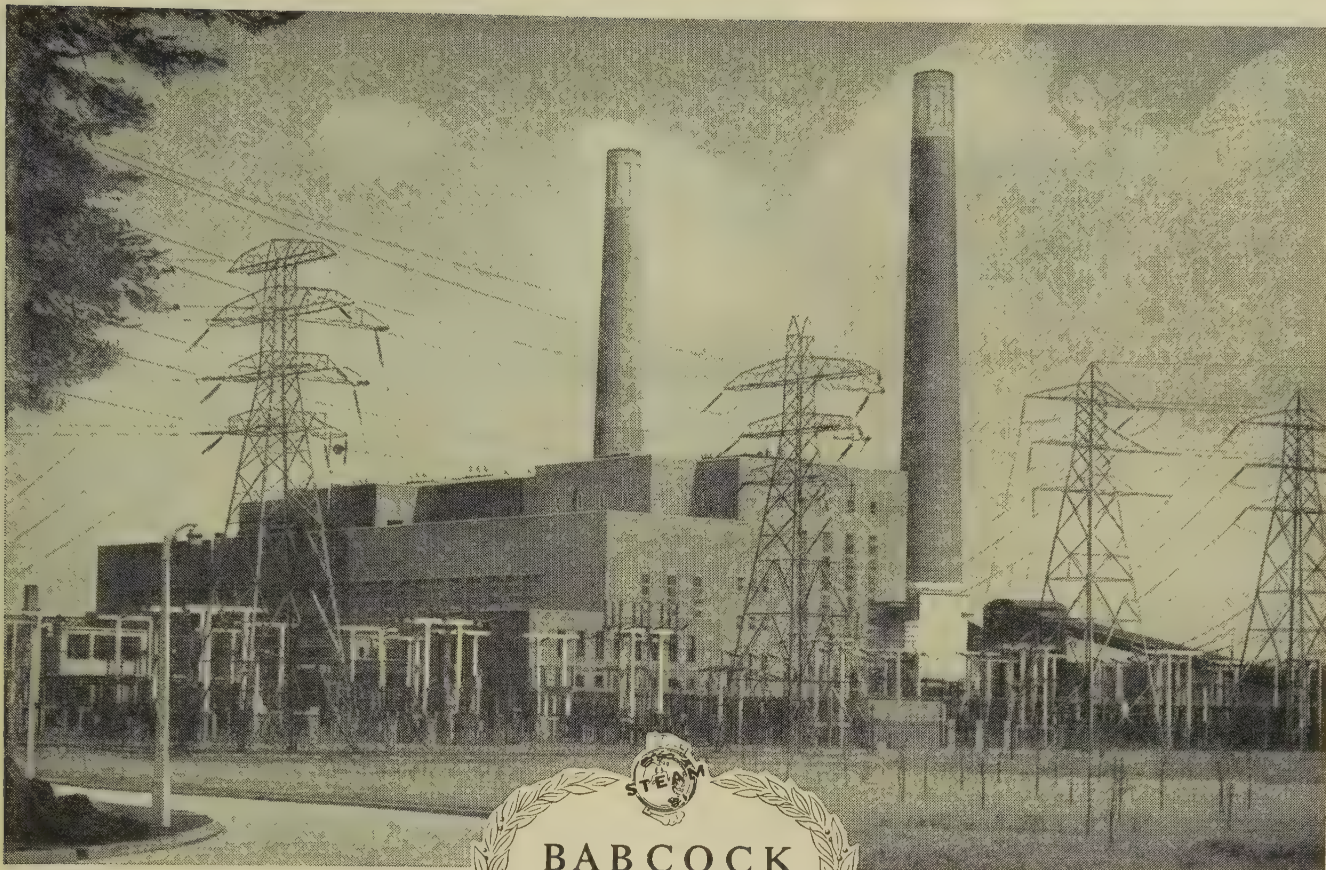

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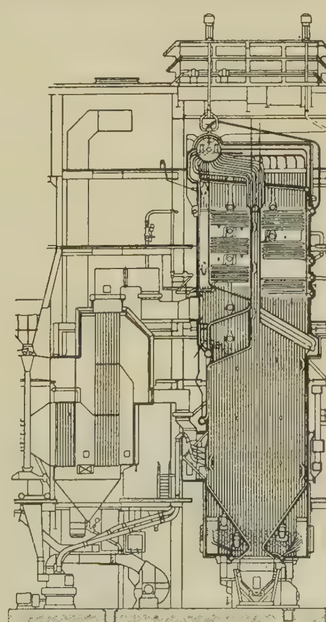

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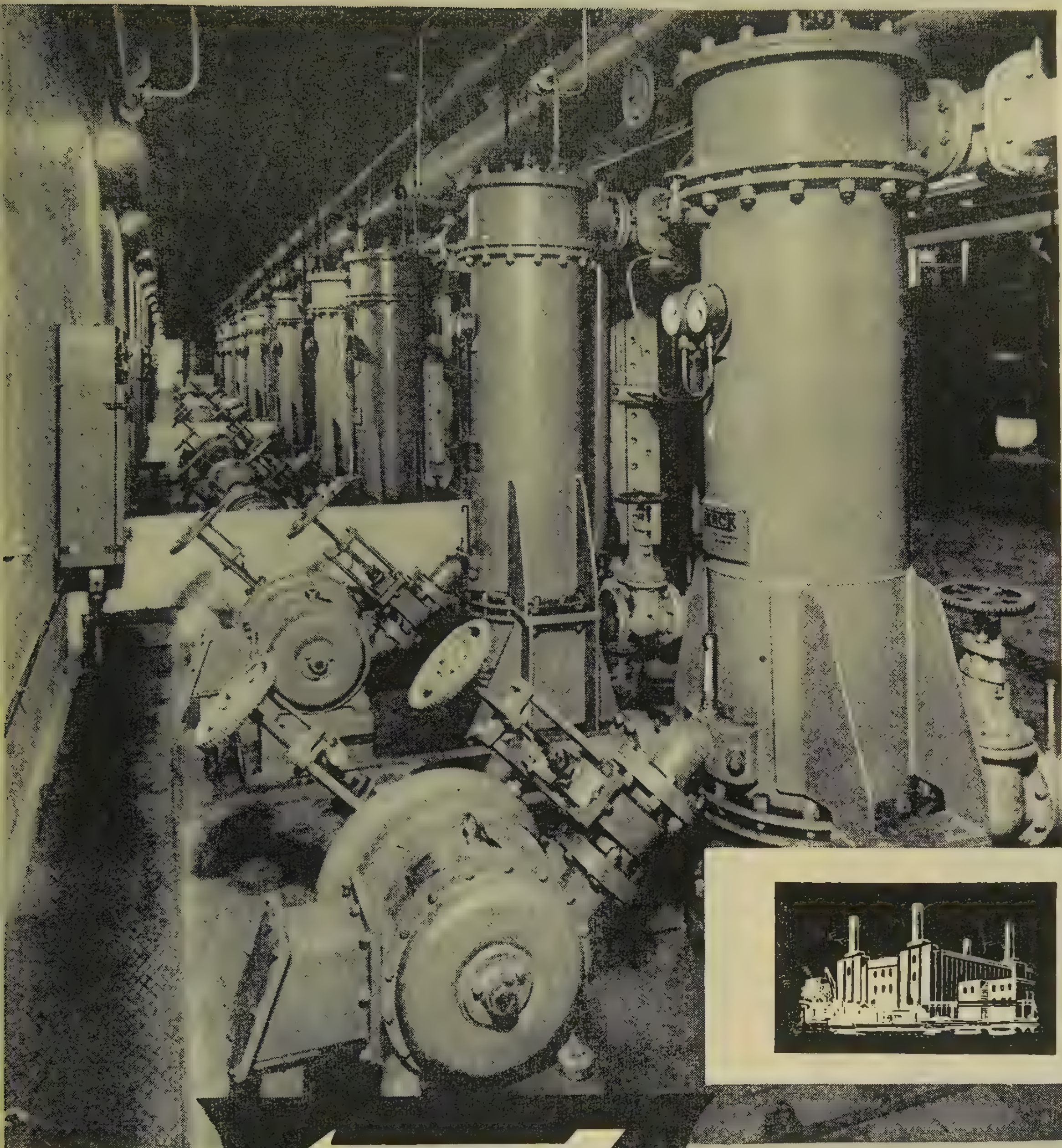

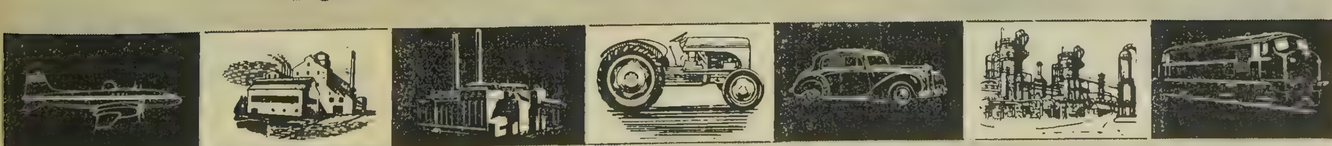

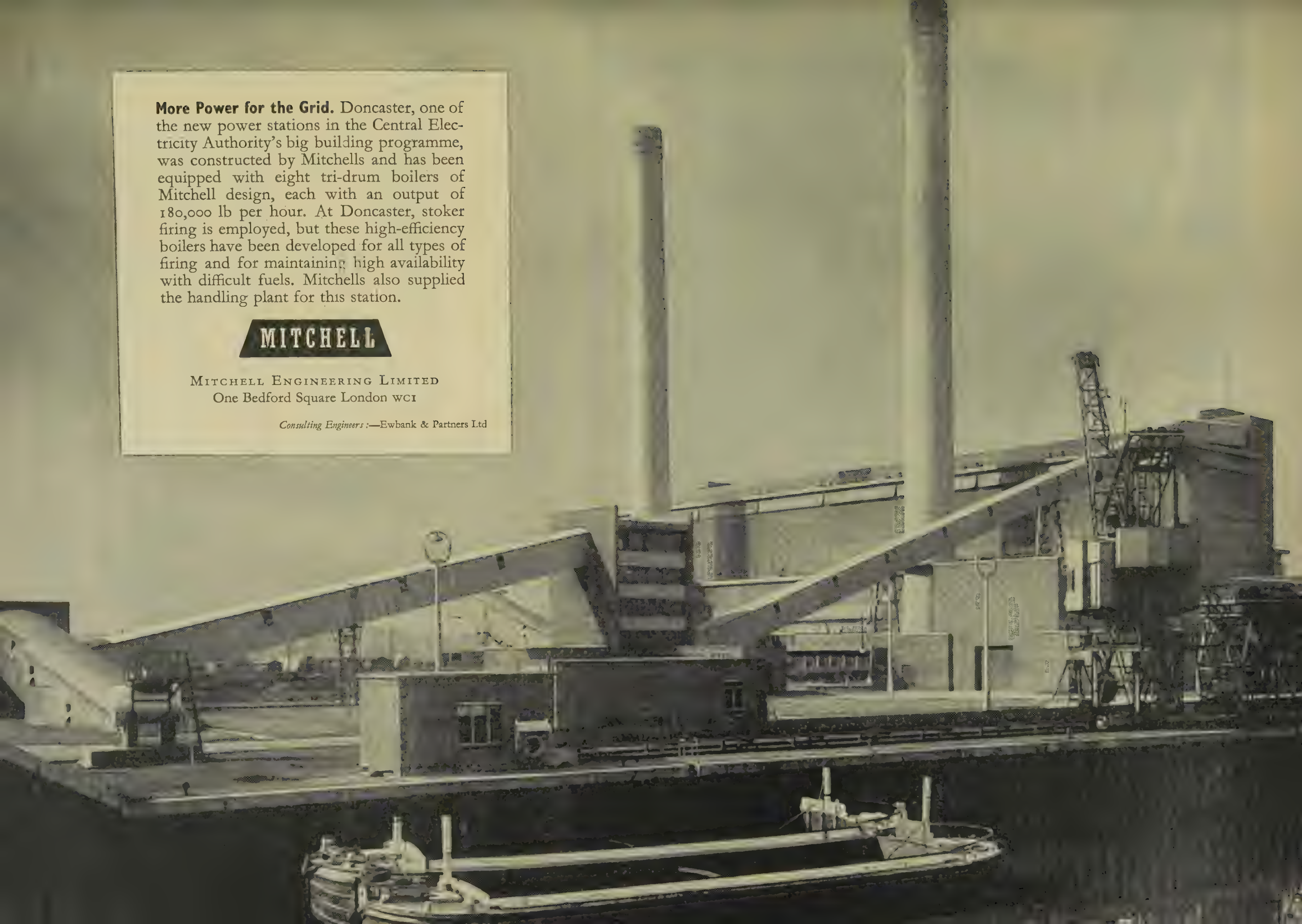

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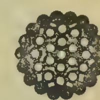

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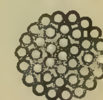

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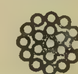

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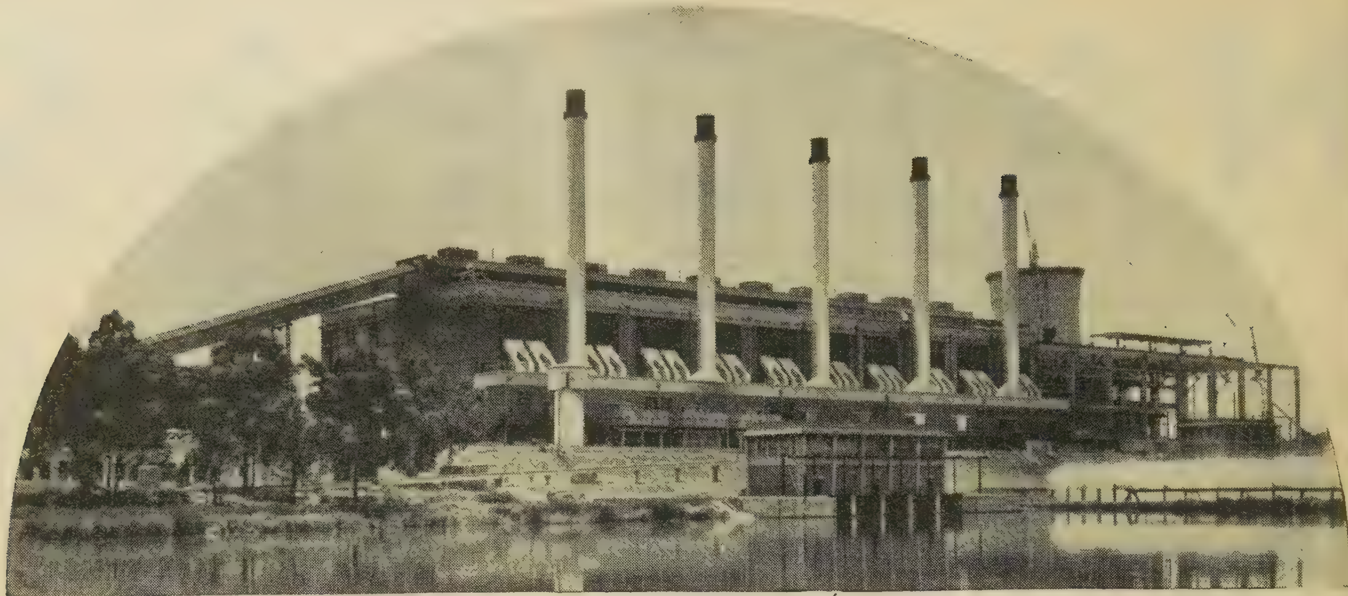

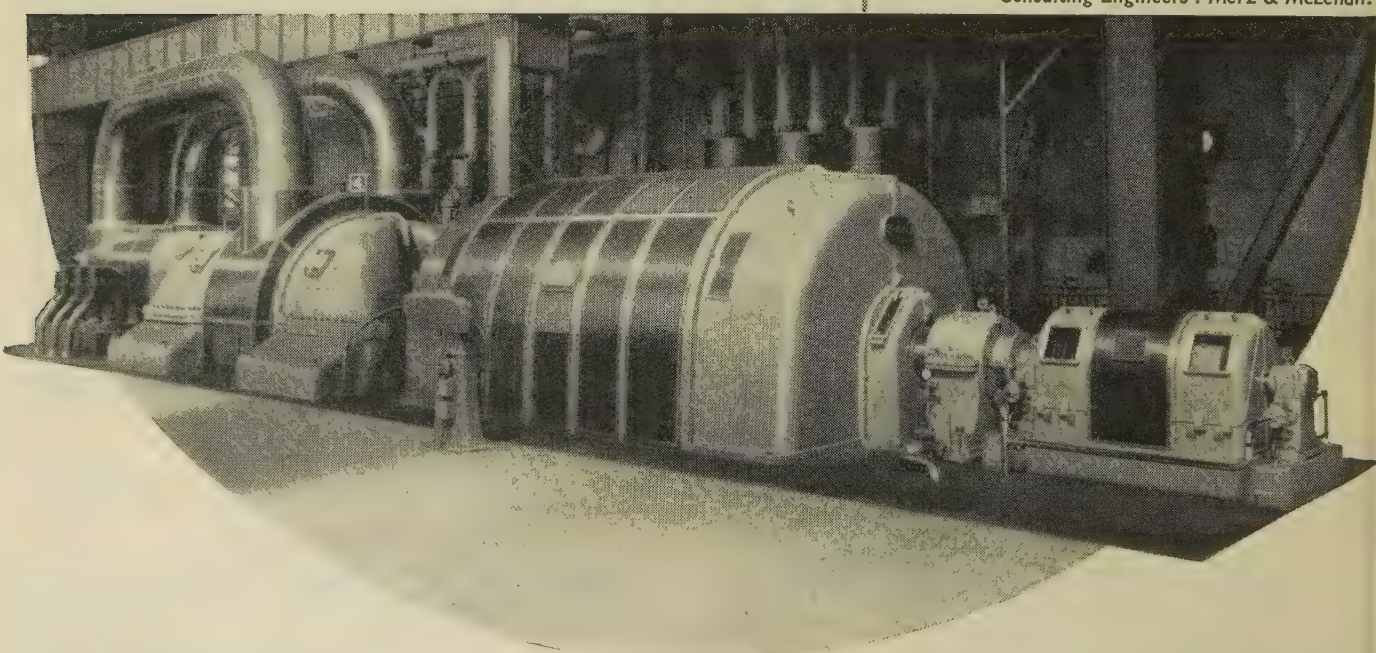

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Paper No. 2168 S
Dec. 1956

VOLTAGE-EXCITATION CHARACTERISTICS OF SYNCHRONOUS MACHINES

By J. H. WALKER, M.Sc., Ph.D., Member.

(*The paper was first received* 14*th April, and in revised form* 18*th June*, 1956.)

SUMMARY

The voltage-excitation characteristics of synchronous machines may be calculated by either cylindrical-rotor or two-axis theory and in each case saturation effects may or may not be included. In order to evaluate the extent to which these methods are applicable to specific cases, six machines are considered—three turbo-alternators and three salient-pole alternators—covering a range of synchronous reactances from 0·7 p.u. to 1·75 p.u. and a range of saturation factors from 1·6 to 2·2.

The errors involved in the use of the various methods are evaluated, and recommendations are made concerning the most suitable methods for calculating these voltage-excitation characteristics.

(1) INTRODUCTION

The size and complexity of modern power systems require an accurate and detailed knowledge of the characteristics of the associated generators. One such set of characteristics, known as the voltage-excitation characteristics or load-magnetization curves, is essential for an assessment of the generator performance, usually with rated armature current, at varying terminal voltage and power factor.

The paper is intended briefly to indicate the various methods of calculating these curves and to compare the accuracy of the results obtained by their use.

(2) GENERAL

The synchronous generators in use in large power stations are of two types:

(*a*) The turbo-alternator or cylindrical-rotor type.
(*b*) The salient-pole type.

As is well known, the calculation of the characteristics of the turbo-alternator is carried out by the so-called cylindrical-rotor theory and that of the salient-pole alternator by the two-axis theory.[1,2,3]

In both cases the effects of saturation in the magnetic circuit of the alternator must be included to obtain accurate results; neglect of saturation, although considerably simplifying the calculation, involves errors the magnitude of which is further affected by the values of the synchronous reactances (X_d and X_q) of the machine. In order, therefore, to obtain reasonably general results the six machines given in Table 1 are considered here. Finally, although the paper is concerned with generators only, the analysis and conclusions apply with equal force to synchronous motors having reactances and saturation factors within the range of those given in Table 1.

Table 1

Item	Type of alternator	X_d	X_q	Saturation factor*
		p.u.	p.u.	
A	Turbo	0·7	—	1·57
B	Turbo	1·0	—	1·75
C	Turbo	1·75	—	2·24
D	Salient-pole	0·7	0·45	1·57
E	Salient-pole	1·0	0·64	1·75
F	Salient-pole	1·75	1·12	2·24

* The saturation factor at rated voltage is defined as $1/(1 - V')$, where V' is the intercept, on the y-axis of the open-circuit magnetization curve, of the tangent to this curve at $V = 1 \cdot 0$ p.u. The figures given in this column represent the normal degree of saturation in a large high-voltage alternator.

(3) COMPARISON OF METHODS FOR CALCULATING VOLTAGE-EXCITATION CHARACTERISTICS

(3.1) The Turbo-Alternator

Voltage-excitation characteristics were calculated by cylindrical-rotor theory for items A to C, including and excluding the effects of magnetic saturation; those for item B, including the effects of saturation, are shown in full lines in Fig. 1. The dotted lines for 0·9 lagging power factor, for 0·5 leading power factor and for the stability limit show the effect of neglecting saturation.

(3.1.1) The Lagging-Power-Factor Range

In the region of lagging power factors the main concern of the designer is the accurate prediction of the field current at rated voltage, armature current and power factor. If, on the

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
Dr. Walker is with the British Thomson-Houston Co. Ltd.

one hand, the predicted field current is appreciably less than that obtained on test there is a danger that the temperature rise of the field windings may exceed that guaranteed. On the other hand, if the predicted field current is appreciably greater than the test value the temperature rise may be substantially lower than that guaranteed and the machine has thus been made larger than necessary. Similar remarks apply to the excitation system supplying the alternator field.

The effect of neglecting saturation can be shown by comparing the dotted and full lines for a power factor of 0·9 in Fig. 1. The field current obtained by neglecting saturation is about 12% less than the accurate value, which represents an increase in the

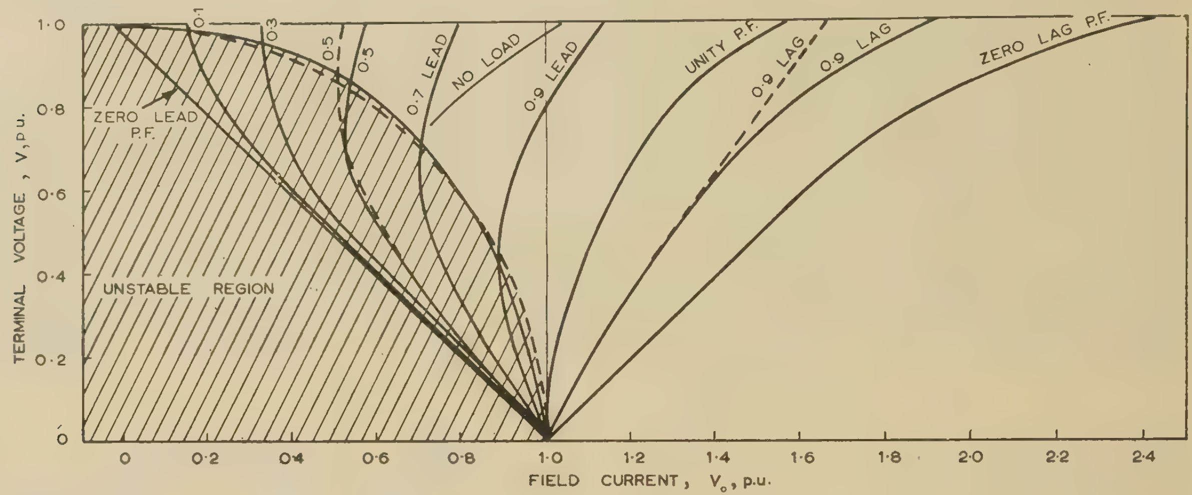

Fig 1.—Turbo-alternator (item B of Table 1).

Voltage-excitation characteristics for $X_d = 1 \cdot 0$ and rated armature current.
———— Including saturation effects.
— — — — Excluding saturation effects.

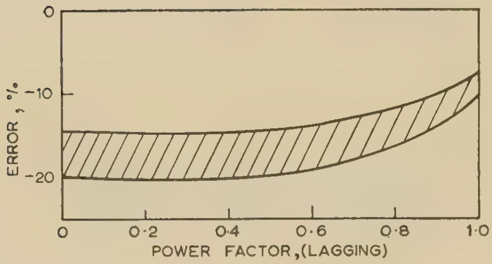

Fig 2.—Turbo-alternator (items A–C of Table 1).

Error in field current, for rated armature voltage and current, calculated by cylindrical-rotor theory, neglecting saturation.

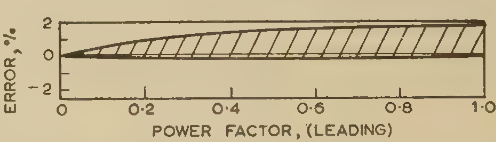

Fig 3.—Turbo-alternator (items A–C of Table 1).

Error in minimum stable voltage, for rated armature current, calculated by cylindrical-rotor theory, neglecting saturation.

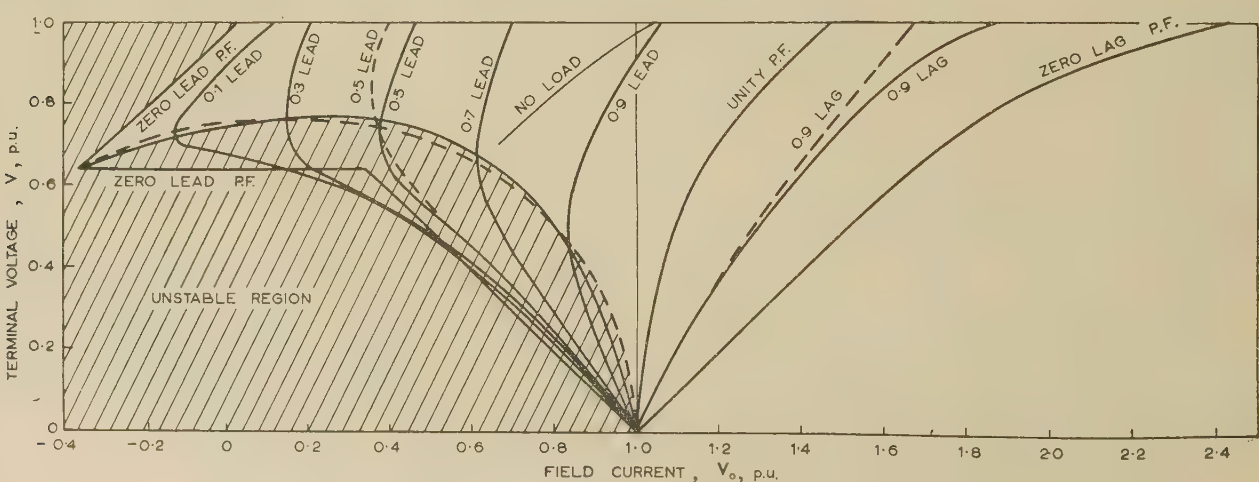

Fig 4.—Salient-pole alternator (item E of Table 1).

Voltage-excitation characteristics for $X_d = 1 \cdot 0$, $X_q = 0 \cdot 64$ and rated armature current.
———— Including saturation effects.
— — — Exluding saturation effects.

temperature rise of the field coils of nearly 30%. This is, of course, not permissible, and the longer but accurate method which includes saturation must therefore be used. The range of corresponding errors for items A–C are shown by the shaded region* in Fig. 2.

From this it can be seen that at unity power factor the predicted field current may be from 8 to 10% lower than the actual current, whilst at zero power factor the error lies between 15 and 20%, depending in both cases on the synchronous reactance and the saturation.

Thus, neglect of saturation involves substantial errors over the whole range of power factors.

(3.1.2) The Leading-Power-Factor Range

In this region of Fig. 1 accurate prediction of the field current is unimportant, since it is always less than the value required for rated load, although it may have some little importance from the point of view of the minimum field current to be handled by the excitation system, automatic voltage-regulator and current limiter.

It is, however, important here accurately to predict the minimum value of voltage (for a given value of armature current and power factor) at which the machine will continue in stable operation. These voltages are given in Fig. 1 by the intersection of the full-line voltage-excitation characteristics with the curved boundary of the unstable region. The corresponding boundary calculated by neglecting saturation is shown by the dotted curve. It can be seen that the minimum voltage at, e.g., 0·5 leading power factor for stable operation, including saturation, is 0·865 p.u. and 0·86 p.u., neglecting saturation, a difference which is negligible. As in the previous case, the range of errors for items A–C has been calculated and is represented by the shaded area in Fig. 3. It can be seen from this that over the given range of parameters the error varies from nil at zero leading power factor to about +1·5% approaching unity power factor. These errors are, of course, quite unimportant in practical applications.

(3.2) The Salient-Pole Alternator

Voltage-excitation characteristics were calculated by two-axis theory for item E, including the effect of saturation, and are shown in full lines in Fig. 4. The dotted lines for 0·9 lagging power factor and 0·5 leading power factor and also for the stability limit again show the effect of neglecting saturation.

In the case of the salient-pole alternator there is a further factor to be taken into account. The use of the two-axis theory in calculating voltage-excitation characteristics is a laborious process when saturation is taken into account. There has therefore been a tendency on the part of many designers to use cylindrical-rotor theory, including saturation, for salient-pole alternators, in order to shorten the labour of calculation.

To assess the errors involved in these various procedures, the voltage-excitation characteristics for items D–F have been calculated by both two-axis and cylindrical-rotor theories, in each case with and without the effects of magnetic saturation. The results obtained by two-axis theory, including the effects of saturation, have been taken as the accurate reference values.

(3.2.1) The Lagging-Power-Factor Range

The values obtained for the field current at rated load and power factor by two-axis and cylindrical-rotor theories neglecting saturation, and also by cylindrical-rotor theory including saturation, were compared with the corresponding accurate reference values and the differences plotted as percentage errors, as shown in Fig. 5. The shaded area in Fig. 5(*a*) shows the amount by which the field currents, calculated by cylindrical-rotor theory including the effect of saturation, differ from the

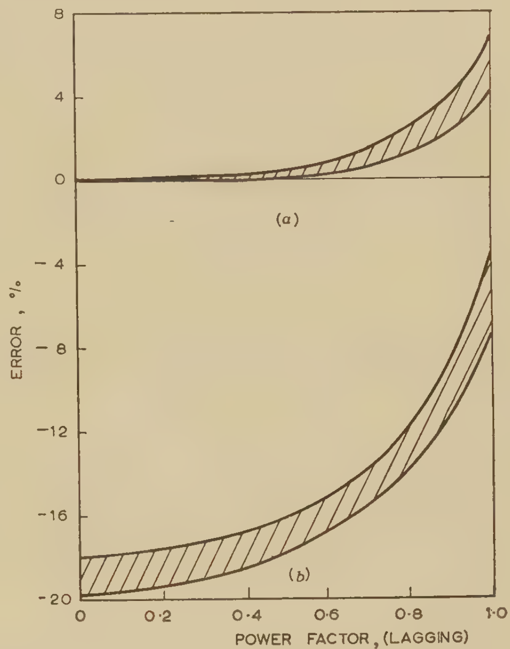

Fig 5.—Salient-pole alternator (items D–F of Table 1).

Error in field current, for rated armature voltage and current.
(*a*) Calculated by cylindrical-rotor theory, including saturation effects.
(*b*) Calculated by cylindrical-rotor and two-axis theories neglecting saturation in each case.

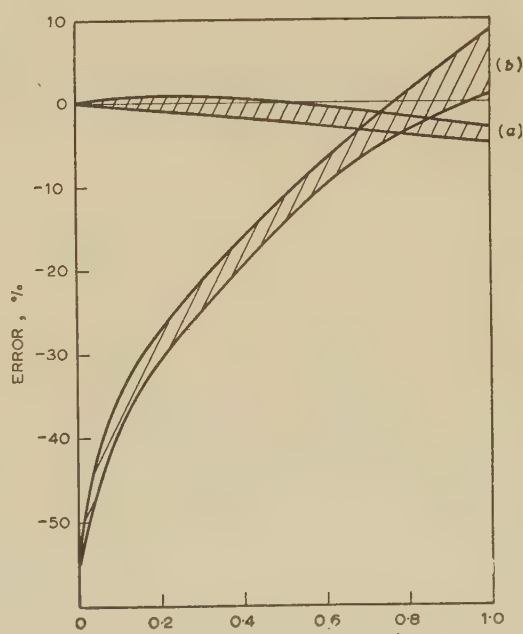

Fig 6.—Salient-pole alternator (items D–F of Table 1).

Error in minimum stable voltage, for rated armature current.
(*a*) Calculated by two-axis theory, neglecting saturation.
(*b*) Calculated by cylindrical-rotor theory, including and neglecting saturation effects.

* In Figs. 2, 3, 5 and 6, the errors for each of items A–F follow smooth curves which lie close to one another and cross each other at more than one point. For the sake of clarity, therefore, shaded areas covering all the points on these curves have been substituted for the curves themselves.

Table 2

Type of alternator	Characteristic to be calculated	Approximate method to simplify calculation	Mean error in approximate method	Accurate method of calculation
Turbo	Field current on load in lagging-power-factor region	Same as accurate method	% None	Cylindrical-rotor theory including saturation effects
	Minimum armature voltage for stable operation in leading-power-factor region	Cylindrical-rotor theory excluding saturation effects	0 to +0·75	
Salient-pole	Field current on load in lagging-power-factor region	Cylindrical-rotor theory including saturation effects	0 to +5·0	Two-axis theory including saturation effects
	Minimum armature voltage for stable operation in leading-power-factor region	Two-axis theory excluding saturation effects	0 to −4·0	

accurate value. Since the mean error varies from about 5% at unity power factor to nil at zero power factor it follows that the use of cylindrical-rotor theory including saturation, for the calculation of field current, is permissible for salient-pole alternators.

The shaded area of Fig. 5(*b*) shows the errors involved in using either two-axis or cylindrical-rotor theory, excluding the effect of saturation. It can at once be seen that with a mean error of about 6% at unity power factor rising to about 19% at zero power factor, neither method is of value for predicting field current.

(3.2.2) The Leading-Power-Factor Range

As already stated, in the leading-power-factor range the main problem is the accurate prediction of the minimum voltage (for a given armature current and power factor) at which stable operation is assured. In Fig. 6 the shaded area (*a*) represents the deviation from the accurate value of this voltage when calculated by the two-axis theory, but excluding saturation. Here the mean error varies from about 4% approaching unity power factor to nil at zero power factor, so that this method is quite satisfactory for practical calculations. The shaded area (*b*) in Fig. 6 gives the corresponding errors if cylindrical-rotor theory, with or without saturation, is used for calculating the minimum voltage for stable operation. It can be seen that the mean errors vary from about +5% approaching unity power factor to −55% at zero power factor, so that, except possibly for a small region between 0·65 power factor and unity power factor, neither method is of any practical value.

(4) CONCLUSION

The results of this analysis of the relative values of the various methods of calculating the voltage-excitation characteristics of alternators are summarized in Table 2 and require no further discussion.

(5) ACKNOWLEDGMENTS

The author is indebted to the Directors of the British Thomson-Houston Co. Ltd., for permission to publish the paper.

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Paper No. 2106 U
May 1956

MINE LOCOMOTIVES

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SUMMARY

This paper reviews the conditions and restrictions governing the use of locomotives in British coal mines, and the designs which have been evolved to meet them. The various types of locomotive are briefly described and some of the principal factors which determine the design of the locomotive are discussed.

The Diesel engine, electrical equipment and power-transmission gear are considered, and particular attention is paid to braking problems and couplings.

Operational experience, with a brief account of some important difficulties and the method of their solution, is included.

An attempt is made to summarize the present position, to indicate the immediate problems which must be solved and to suggest further long-term lines of progress.

DEFINITIONS OF TERMS

Two or three terms which are in common use in mines may require definition.

The *inbye* end of a mine road is that end furthest from the pit bottom, and the *outbye* end is that end nearest the pit bottom. A *passbye* track is a section of double track connecting lengths of single track and providing facilities for trains to pass. Self-evident derivatives are the inbye and outbye ends of the passbye.

The *dip* of a seam or road is the angle with the horizontal; *dipping inbye* means going downhill as one moves into the mine from the pit bottom.

The *intake airway* is the road carrying the ventilating air stream from the shaft to the working faces; the *return airway* is the road along which it returns.

(1) INTRODUCTION

During the last 15 years over 800 electric-battery and Diesel locomotives, spread over about 40 different designs, have been put to work in British coal mines, 600 of them since the creation of the National Coal Board in 1947. In round figures about 25% are battery and 75% Diesel, and the rate of introduction of the two types is shown in Fig. 1. During this period a great deal of work has been done, both by manufacturers and users, in studying the operating conditions and evolving designs to meet them. Difficulties have been experienced, some of them of a serious character, but they have been surmounted and the use of locomotives underground has steadily increased. Even so, the amount of coal transported underground in locomotive-hauled trains is still less than 20%. Therefore, whilst much has been done, an immense field awaits investigation.

Mine locomotives, of whatever type, offer certain specific advantages over the two alternatives which are available, namely rope haulage and belt conveyors. They have a flexibility of operation which neither of these possesses, and whilst their superiority has to be established for every individual case, it is exactly on this basis that their use is steadily extending.

The whole field of underground transport is particularly fluid,

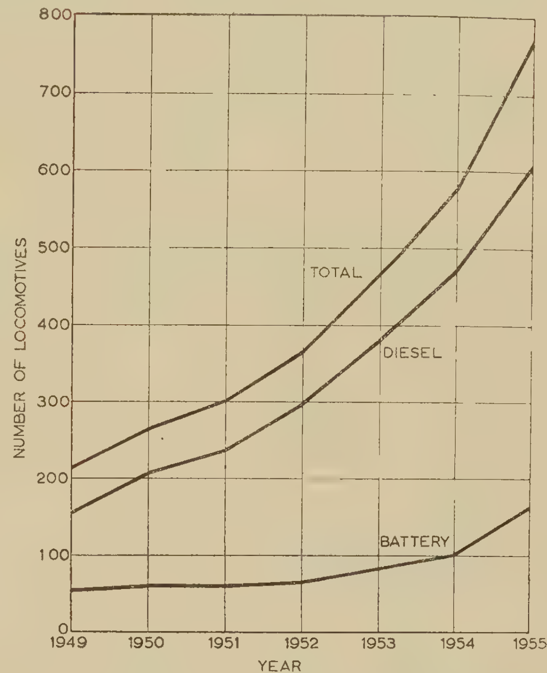


Fig. 1.—Number of locomotives in British coal mines.
Returns are at the 30th June every year.

which at this stage is a healthy sign. Mines are being rebuilt; methods and rates of getting coal are rapidly changing and the transportation problem is correspondingly affected. The fact that over 30 designs of locomotive have been developed in the last eight years or so is evidence of a keen perception amongst locomotive builders, nor is there any sign of an end being reached. The plain fact is that we have no type or design which is outstandingly superior and suitable for the duty. All have some serious limitation. Consequently the search for some alternative form of motive power, or, in wider terms, for some more efficient method of transporting coal, men and materials underground, goes forward incessantly. It is by no means fanciful to state that an outstanding advance in locomotive design or transportation technique could alter the whole picture and sweep the entire field clean. But the problem is particularly difficult, because of the extensive restrictions and limitations.

Two factors which exercise immense influence over the general design and operation of all mine locomotives are safety and simplicity. The N.C.B. cannot adopt any other than the highest standards of safety, and many developments otherwise beneficial are excluded because they would introduce an unacceptable hazard. It is a truism that all engineering equipment should be made as simple as possible, but for mining equipment the attitude is much more positive. The worth of any complication must be fully established before it can be accepted. In addition, there is a cardinal rule which is rarely if ever broken, and which also influences the design and use of locomotives in mines—any failure must be a 'failure to safety'.

This is an 'integrating' paper. Members are invited to submit papers in this category, giving the full perspective of the developments leading to the present practice in a particular part of one of the branches of electrical science.

Mr. Green is with the National Coal Board.

The earliest designs, which incidentally still hold their place, were naturally small in weight and power; up to about 7 tons and 50 h.p. with a driving cab or well at one end. Developments in the mining of coal, and increasing demands for more efficient haulage systems, resulted in heavier and more powerful units being designed and installed, but at a somewhat slower rate, since corresponding advances in the standard of the track and wider and higher roadways were essential. The driving of wide roads is particularly costly, and for some years the maximum size of locomotive has remained at 15 tons 100 h.p. operating on 3 ft 6 in gauge track,* double heading rather than bigger locomotives being resorted to in those cases where greater power is needed. The main trend during the last year or two has been in making existing designs safer and more efficient. Practically all the designs introduced during the last four or five years have a driving position at each end—an important development referred to in Section 2.3.

(2) LIMITING CONDITIONS

The use of locomotives in British coal mines is limited by the physical conditions of the mine and by statutory regulations which are enforced by the Health and Safety Division of the Ministry of Fuel and Power† to ensure a high standard of safety.

(2.1) Mining Conditions

The physical conditions of the haulage roads of the mine which influence the design and operation of the locomotives are

(*a*) The shape and size of the cross-sectional area.
(*b*) The gradient.
(*c*) The minimum radius of curvature.
(*d*) The stability of the surrounding strata.
(*e*) The ambient temperature.
(*f*) The ventilating air stream.

All these factors are closely bound up with the age and history of the mine itself. In many of the older mines the layout and disposition of the haulage roads is simply the result of the traditional British method of mining 'in the seam'. Wherever the seam of coal has led the road has been driven, and since many of the coal measures in this country are more or less steeply inclined, the resulting roads may be at gradients up to as much as 1 in 2 or 1 in 3. Since also the natural tendency has been to take the coal from the shallowest seams first, the roads tend to dip as the workings are extended. In these older mines the roads are usually small in comparison with present-day standards and are often only sufficient for a single haulage track. The maximum gradients worked by locomotives are about 1 in 20, and these older mine roads often include curves with a radius of as little as 25 or 30 ft which could be increased only at very considerable expense.

In the new mines which are now being planned and constructed some variant of horizon mining is usually adopted, and haulage roads wide enough to accommodate double tracks of up to 3 ft gauge are driven at a gradient lying between about 1 in 250 and 1 in 500, whilst any curves can usually be made of adequate radius, namely 80 or 100 ft. Under these conditions efficient locomotive installations can be planned.

Unfortunately the rebuilding of the mines which is in progress often involves linking together several old networks of roads by newer and larger drivages, with some enlargement and regrading of the more important of the existing roads. The extent to which this can be done depends on the capital expenditure which can be justified. The result, from a traction point of view, is often a complicated and widely varying set of haulage conditions. The layout of the haulage roads for a group of mines reconstructed in this way is shown in Fig. 2; it will be noted the gradients vary from 1 in 43 to level; most of the older roads are adequate only for a single track.

In practically all cases the mine roads are so narrow as entirely to preclude turning the locomotive in them.

The layout round the pit bottom usually includes a loop which would enable the locomotive to be turned if desired. A common cycle of operation, however, provides for the locomotive to bring its full train to the entrance to the pit bottom, detach there and then return immediately inbye with an empty train. It thus makes no use of this facility, nor would there be much point in doing so, since there is no corresponding provision at the inbye end. Therefore, in the great majority of cases the locomotive simply shuttles backwards and forwards along the mine road—a factor which has had considerable influence on the designs.

The instability of mine roads presents a constant problem. Under the pressures of the surrounding strata the floor, sides and roof are always tending to move towards each other. Where this movement is slight the mining engineer refers to his road conditions as 'good' or 'stable', but it is invariably enough to render it impossible to maintain a well-aligned track. In 'moving ground' the conditions are greatly worsened.

A general consequence of these road conditions is, first, the limitation of the maximum weight of locomotive to about 15 tons, and secondly, whilst maximum speeds of 16–18 m.p.h. may be possible on a few stable and well-maintained roads, a great deal of running in a mine is done at, say, 8 m.p.h. or less. This latter factor is pertinent in a variety of ways. For example, braking a train on the surface from a speed of, say, 5 m.p.h. is usually of little consequence; it is a vital problem in a mine.

The ambient temperature in the mine road depends principally on the temperature of ventilating air drawn in from the surface. It will therefore vary widely between summer and winter but not so much over a consecutive 24 hours. This ventilating air stream constitutes a further physical factor which has presented a number of problems. It is of considerable force—the rate of flow may exceed 600 ft/min—and where the mine roads are stone-dusted it can hold much of this dust in suspension. This must therefore be regarded as a normal environmental condition and locomotives must be suitable for operation in it. An investigation into the dust conditions in a main haulage road showed the percentage particle size to be: 95% from 1 to 5 microns, 4% from 5 to 25 microns and the remaining 1% over 25 microns; the total number of particles per cubic centimetre over 1 micron was 180.

It should be emphasized that conditions vary widely, but the figures quoted and the high proportion of the 1–5-micron group, in particular, are representative.

(2.2) Regulations

There are several documents governing the use of locomotives underground, based essentially on the physical mining conditions but primarily aimed at ensuring the maximum practicable degree of safety, which collectively form a fairly rigid framework. They are as follows:

The Coal Mines (Locomotives) General Regulations 1949, S.I. No. 530.*

Testing Memorandum No. 11. Tests and Specifications for Storage Battery Locomotives.

H/S. 407/59. Diesel Engine Locomotives for use in Coal Mines: Requirements as to design, construction and official test.

The details, which relate to the design, construction, operation and maintenance, may be studied in the documents themselves.

* The recommended gauges for future adoption are 2 ft 0 in, 2 ft 6 in, 3 ft 0 in, and 3 ft 6 in. There are many mines using the first two, and a large number of new schemes include 3 ft 0 in gauge track. Only a small number have installed 3 ft 6 in, and since double tracks of this gauge necessitate a minimum road width of 15 ft, such propositions have to be very carefully scrutinized.

† Hereafter referred to as the 'Inspectorate'.

* Hereafter referred to as the 'General Locomotive Regulations'.

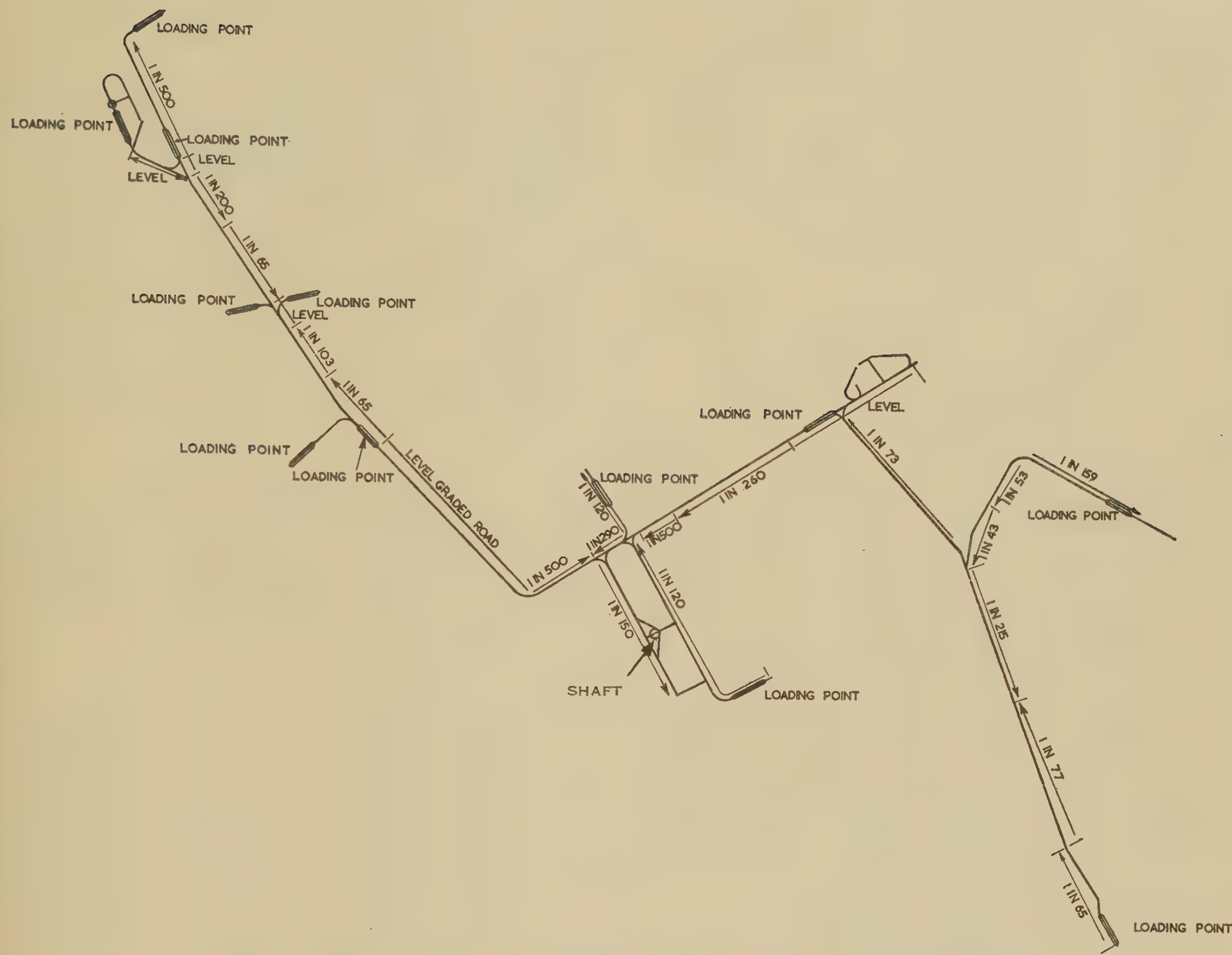


Fig. 2.—Layout of haulage roads in a reconstructed mine. (Hawthorn mine, Durham.)
The arrows point downhill.

Broadly, all locomotives must be of an approved type; with this proviso, battery and Diesel locomotives may be used anywhere in the mine by permission of the Inspector of the Division.* Electric trolley or pantograph locomotives must conform to the general regulations, but in addition they must comply with any special regulations which might be imposed and which are established for each mine separately.

Since battery and Diesel locomotives are likely to be used anywhere in the mine they are always made to comply with flameproof conditions. If their use, in any given instance, were restricted to an intake airway, not nearer than 300 yd to a working face, such locomotives need not be made flameproof. However, since locomotives can be taken wherever there are suitable tracks the possibility of a non-flameproof locomotive being operated in a danger zone, whatever rules are laid down, is too great a hazard, and the N.C.B. has never attempted to take advantage of this theoretical possibility. All Diesel and battery locomotives working in safety-lamp mines, whatever the limits set on their operation, are of approved flameproof types.

Pantograph locomotives need not be made flameproof, their use being restricted by the extent of the overhead wire. Open sparking cannot altogether be eliminated.

All locomotives must be constructed, as far as possible, of non-inflammable material. In the case of a Diesel locomotive the combustion and exhaust system must constitute a flameproof unit to the requirements of B.S. 229 (Flameproof Enclosure of Electrical Apparatus). In practice this has usually meant the provision of inlet and exhaust flametraps, and some equipment, usually a water box, for cooling and diluting the exhaust gases; where reliance is placed on water an interlocking arrangement must also be included which will cut off the fuel supply to the engine if the water falls below a predetermined level. Because of their lethal qualities, carbon monoxide and oxides of nitrogen are dangerous, and the permissible content of both is specifically restricted. Every locomotive must have direct mechanical brakes in addition to any other type, and must be provided with the following auxiliary equipment: sanding gear, a combined speedometer and mileage indicator, a headlight, a warning signal, a portable fire extinguisher, a portable lamp, and a seat for the driver.

The brakes must be of such a design that locking of the wheels is avoided as far as possible, whilst the brake blocks or linings must be such that the generation of sparks is minimized.

The maximum permissible gradient for Diesel or battery locomotives is 1 in 15, whilst there are specific regulations governing the weight of rail (shown diagrammatically in Fig. 3), distances between sleepers, and clearances between locomotives

* A Division of the Inspectorate, not an N.C.B. Division.

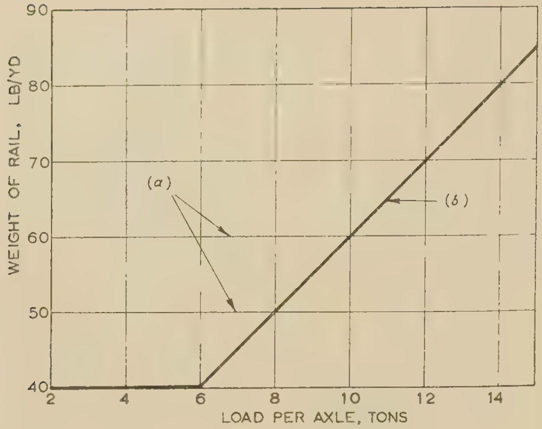


Fig. 3.—Weight of track rails.

(*a*) N.C.B. minimum recommended weights.
(*b*) Regulation 9(3)(*b*).

Regulation 9(3).—The weight of rail per yard of rail shall not be less:

(*a*) If the road is used only for the carriage or haulage of stores or supplies for the working of the mine and no locomotive therein exceeds 5 tons in weight, than 28 lb.
(*b*) In any other case, than 40 lb, or 10 lb with an addition of 5 lb for each ton of weight on one pair of wheels, whichever is the greater.

and the sides and roof of the road. Standards of ventilation are laid down and the proportions of methane gas which necessitate withdrawal of locomotives from service. Minimum requirements for inspection and maintenance are laid down. The persons who may drive are nominated, and the method of operation is specified.

With Diesel locomotives strict conditions relate to the garage and refuelling arrangements, and the charging stations for battery locomotives. The regulations specify in considerable detail the ventilation necessary for the battery, since complete reliance for safety is placed on this method of dispersing the hydrogen.

(2.3) Effect on Locomotive Design

There can be few fields of traction service where locomotive design is more restricted than in mining. The size of the mine road and the provision of the statutory clearances compress the cross-sectional area in a high degree.

The length of a locomotive is capable of some variation, but if excessive, it may prove difficult to lower the unit down the shaft. The smaller sizes will often go inside the cage, but if the locomotive is too long for this it may be slung under the cage, or the cage may be removed and the locomotive suspended directly from the winding rope. Some of the newer designs provide for the locomotive frame to be divided into two parts, or alternatively, for the driving cabs to be removed for transport down the shaft, the unit afterwards being reassembled underground. In any case, whilst this operation is unlikely to occur more than once or twice during the life of the locomotive, excessive length can give rise to an ever-present operational problem owing to lateral throw when negotiating curves of small radius.

Most of the locomotives are simple two-axle designs, but three of the heaviest Diesel locomotives are carried on three axles. When these units were first developed the tracks in mines were just beginning to change over from the light 28 lb/yd rail, which had served the slow-speed rope haulages for so long, to the higher standards demanded by the General Locomotive Regulations. The use of three axles to carry 15 tons enabled the load per axle to be kept down to 5 tons, and without any doubt this enabled the mining industry to gain some valuable experience on the laying of tracks and the maintenance of a standard that was then quite new. During recent years there has been an increasing tendency to adopt 50 or 60 lb/yd rails, and in consequence, the larger battery locomotives (of up to 14 tons weight) have been kept on two axles, the resulting increase in track loading now being acceptable.

The special conditions of operation require much auxiliary equipment, which must be housed, as far as possible, in a manner which permits satisfactory maintenance work to be carried out. Thus the locomotive, as finally designed, tends to be a long solid prism, with all the available space packed with equipment. One of the General Locomotive Regulations states that the driver must be able to see ahead without leaning out of the locomotive, and since a design like a solid prism does not permit this, the latest units have been provided with a cab at each end. The second cab is also valuable in that it provides a place for a second person to ride in safety; with the single-cab designs there is no proper accommodation for anyone except the driver, though there are many occasions when a second person may need to ride on the locomotive. These are not trivial details; fatalities have occurred from both causes.

(3) BASIC OPERATING CYCLE

Locomotive duty varies with the conditions at each mine, from short runs of a few hundred yards to journeys of 3 miles or more, taking from 10 to 40 min. The gradients vary from about 1 in 20 to level, with the heavier gradients invariably against the full train. Each mine and each road in the mine must be the subject of a separate investigation.

(4) POSSIBLE TYPES OF LOCOMOTIVE

The General Locomotive Regulations were drafted to enable battery and Diesel locomotives to be used on an extensive scale with a minimum of formality. Other types of locomotive are subject to additional restrictions, so that if they are to be introduced or their use is to be extended, considerable additional difficulties have to be negotiated; this single factor goes a long way towards explaining why alternatives to the battery and Diesel types have been so slow in gaining a footing, even when they had operating or other characteristics that were attractive. The installation of trolley or pantograph locomotives is subject to special regulations being established, but one such set does now exist and may be taken as a good guide for other cases.

At different times compressed-air locomotives, battery-cum-trolley and trolley-cable-reel locomotives have been considered, but the existence of this initial difficulty—the establishment of the regulations under which their use would be permitted—has always acted as a powerful deterrent to the engineers who are struggling to rebuild the industry whilst at the same time maintaining current production.

(4.1) Battery Locomotives

Battery locomotives range in size from 2 tons 5 h.p. to 13 tons 90 h.p. The same general design obtains throughout, with some additional equipment and facilities in the larger sizes. All are carried on two axles, and except for the largest sizes, they have a single driving cab at one end. If the driver's seat and the locomotive controls are so disposed that he has a satisfactory range of vision over the battery box there is no need for the second cab. On the largest units the battery box is of such a size that this is not possible, so that a driving cab is provided at each end. The general arrangement of one of the latest types now being used in increasing numbers is shown in Fig. 4; it will be noted that this provides for both cabs to be removed.

The provision of the second driving cab, simple enough as a feature of the locomotive, may have serious consequential operating difficulties in the mine. It lengthens a unit already uncomfortably long for a mine road by about 3 ft (making an

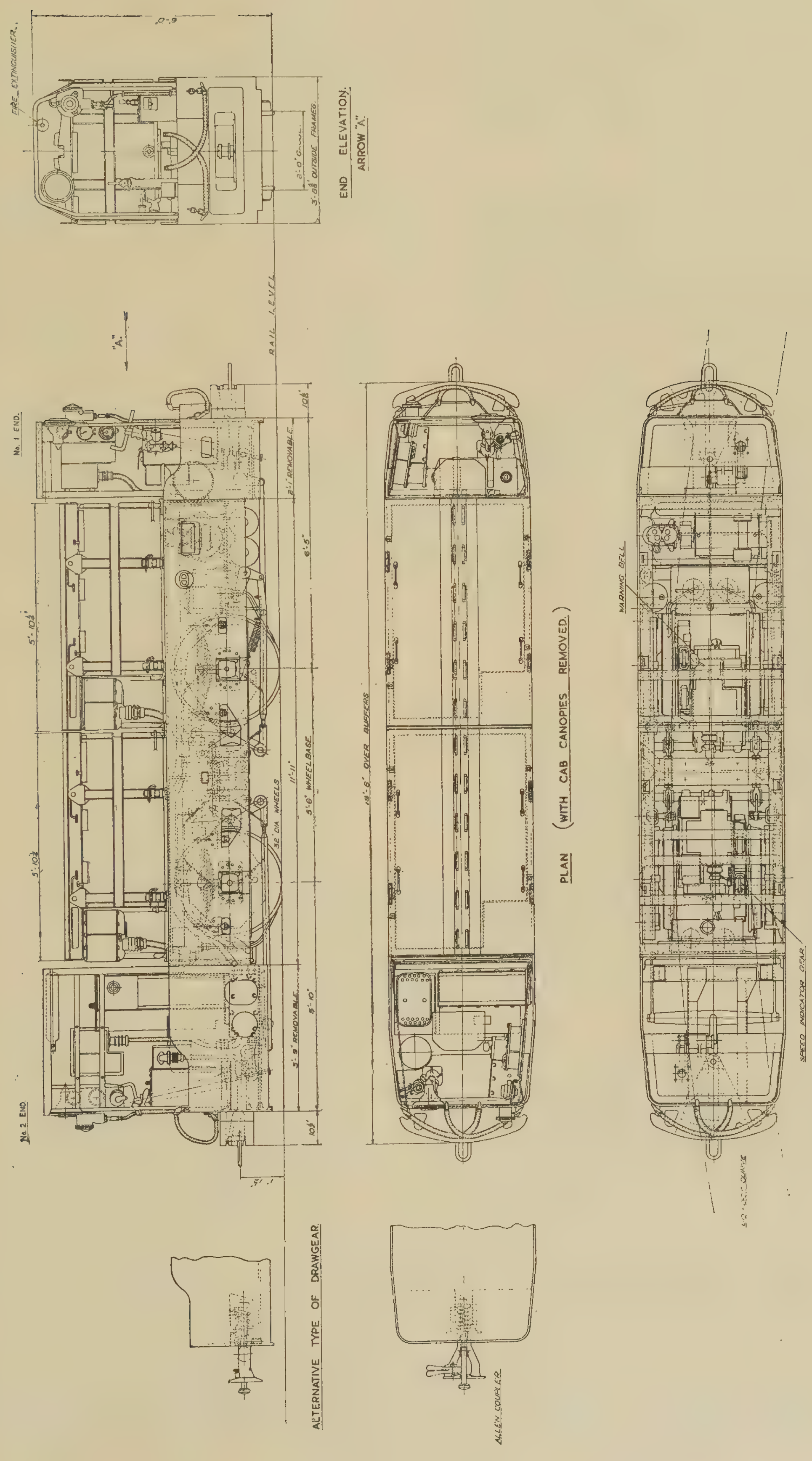


Fig. 4.—General arrangement of underground battery locomotive.

Total weight of locomotive: 12¼ tons.

overall length of 17–18 ft). This, in turn, increases the lateral throw of the couplings on curves and the consequent tendency to derailment. The proportions of wheelbase to overhang shown in Fig. 4 present a constant problem. The former must be kept to a minimum to permit the negotiation of curves of small radius, but the consequence is a corresponding increase in overhang.

(4.2) Diesel Locomotives

Diesel locomotives range from $2\frac{1}{2}$ tons 16 h.p. to 15 tons 100 h.p., all being on two axles except for the 15-ton designs, which, with one exception, are on three axles. This restricts the axle loading to 5 tons, or, in the exception mentioned, to $7\frac{1}{2}$ tons. The use of a single driving cab was general in the early designs, but difficulties in obtaining an adequate range of vision when driving from the rear end have led to the introduction of a double cab on more recent models.

(4.3) Electric Pantograph Locomotives

The use of the trolley type of collector is excluded by the terms of the regulations—hence the more precise, if less usual, title of this Section. The simple construction of the electric pantograph locomotive makes it a particularly attractive unit for mining work, and its limited use appears to be mainly due to the regulations, which are still somewhat onerous.

Since all the equipment, except the pantograph(s), can be accommodated within the side frames and top plate, there is little or no obstruction of the driver's range of sight, even when the driving position is at the rear end of the locomotive, and consequently one cab suffices.

(4.4) Electro-gyro Locomotive

The latest development in mining locomotives is known as the 'electro-gyro unit'. The principle is that of energy stored in a revolving flywheel, but considerable work has been done to make this an efficient and flexible type of motive power. The locomotive is equipped with an a.c. squirrel-cage machine mounted on an extension of the vertical shaft of the flywheel, together with an a.c. traction motor on the locomotive axles. Energy is stored in the flywheel by connecting the squirrel-cage motor to a suitable source of supply, and is afterwards used to drive the locomotive by discharging this energy through the machine on the flywheel shaft, now acting as a generator and supplying current in the usual way to the axle-mounted traction motor. A typical general arrangement is shown in Fig. 5.

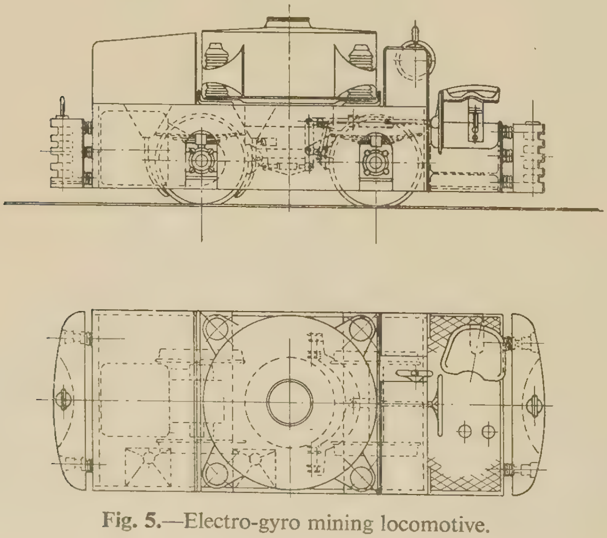


Fig. 5.—Electro-gyro mining locomotive.

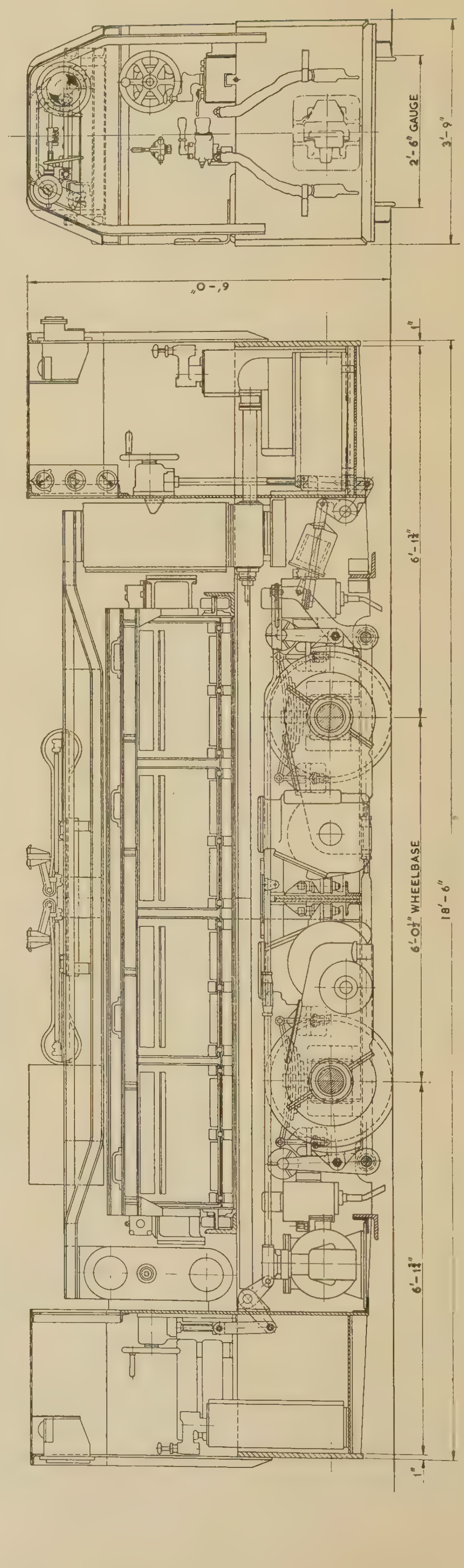


Fig. 6.—Combined battery/trolley locomotive.

Only a few of these locomotives have been built so far, none for use in this country, but the N.C.B. has a surface shunting unit, using the same principle, under construction.

The attraction of this type of unit is that it will operate for some 20–30 min away from the source of supply, and can be easily and quickly re-energized.

(4.5) Battery/Pantograph Locomotives

The attractions of a combined battery/pantograph locomotive are obvious; operation on the pantograph during the long main haul, with a change-over to battery operation for shunting and marshalling work in places where there is no overhead wire, suggests a desirable economy of operation. There is the added attraction that it might be possible to recharge the battery during normal operation from the trolley wire. Much attention has been paid to the problem during recent years, and a number of designs have been prepared, one of which is shown in Fig. 6.

On closer scrutiny a number of difficulties are found to exist. It has been explained in Section 2.2 that battery locomotives must be flameproof whilst pantograph locomotives are not. In the case of a combined unit, for the same reasons, all the equipment must be flameproof. Apart from the increased cost the problem of accommodating still more equipment is an exacting one. It will be noted from Fig. 6 that the pantograph is housed by using a battery of reduced capacity and consequently of lower overall height. This is possible because the battery now has to provide energy only for shunting duty at the ends of the main haul.

There is, however, a further problem referred to in Section 8, namely the necessity of recharging only in the charging station because of the danger of liberated hydrogen. For this reason, recharging whilst operating from the overhead wire is still forbidden.

In spite of these and similar difficulties, a combined unit of the type in question is an obvious development which should soon be realized.

(5) MECHANICAL STRUCTURE

The type of locomotive has only a slight effect on the general design of the mechanical structure. A Diesel engine must be adequately supported, whilst axle-hung traction motors have weights and reactions which must be provided for, but these are mainly questions of detail design. The overriding considerations are simplicity and reasonable cost, so that simple plate-frame box structures are invariably used, suitably tied and gusseted, and with cast-iron or steel headstocks which serve as a buffer beam and an attachment for the wide variety of couplings at present in use.

A typical frame drawing for a 13-ton double-ended battery locomotive is shown in Fig. 7. The amount of equipment which has to be accommodated between the side frames, and the fact that the frame can be divided into two parts for transport down the shaft, makes the disposition of the ties and struts a difficult problem. Obviously, full advantage has been taken of the break across the centre of the frames, where a heavy tie is provided

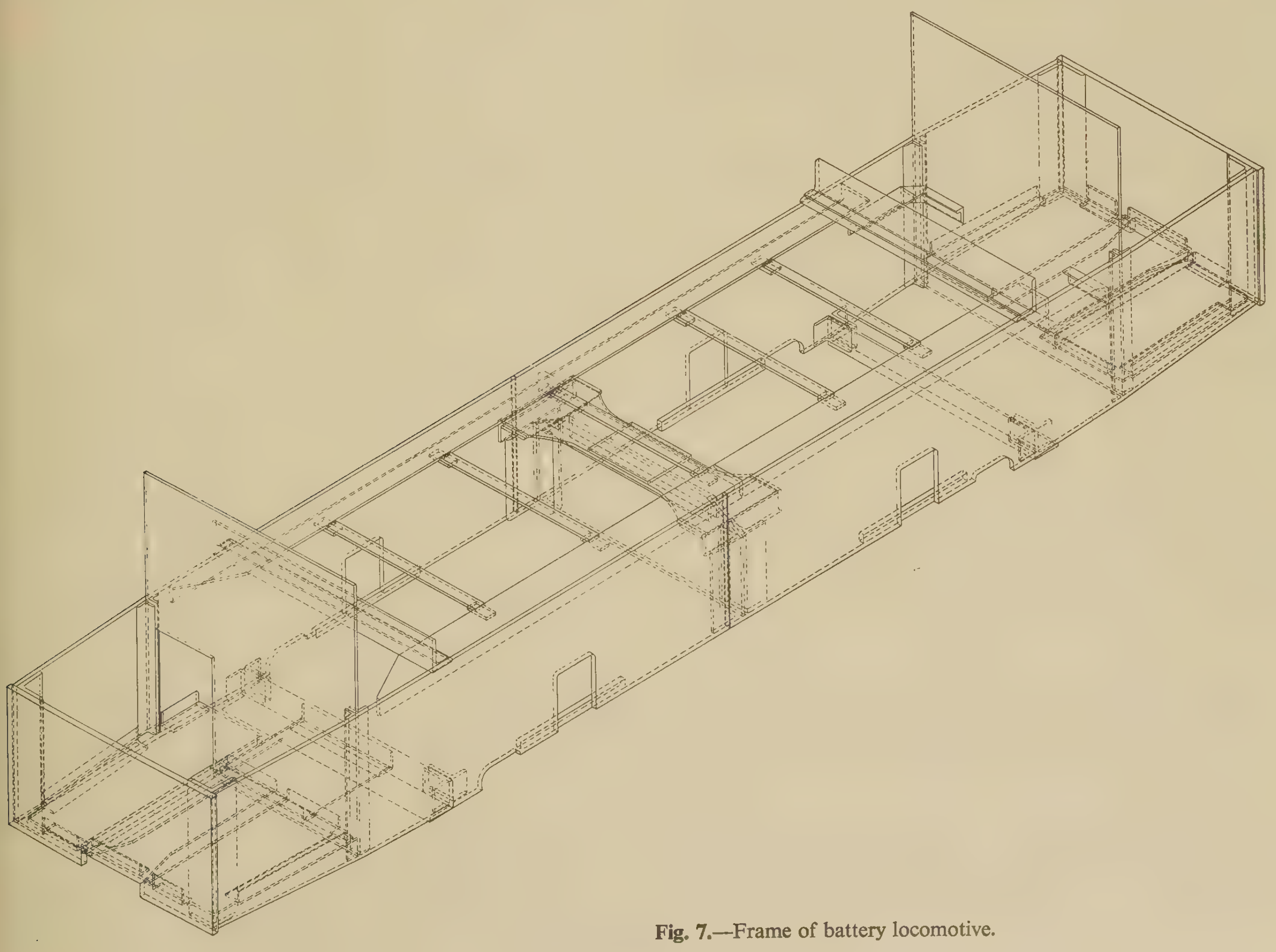


Fig. 7.—Frame of battery locomotive.

spanning the connecting angles, whilst the driving wells at each end also contribute to the general stability. This same member is also used to provide the nose supports for the inward-hung traction motors. The remaining ties are comparatively light, and it is usually found necessary to utilize the equipment frames, e.g. the resistance frames, in some degree. The provision of removable cabs instead of divided main frames has already been referred to in Section 2.3.

Since the space between the two rear cab plates is entirely occupied by the battery containers there is no necessity to plate this over. Removal of the containers at once provides access to the traction motors, cables, brake rigging and all the other equipment.

The stresses due to the loading on the couplings are carried by the box frame; the main frames are of good depth and appear commendably free from weak sections.

Most of the smaller sizes have sleeve bearings, but the increasing weight within the same limited width, whilst still retaining the simple two-axle design, has recently led to the adoption of roller bearings.

The brakes and brake rigging must have their share of the available space, but no design has yet been evolved which provides for braking on both sides of the wheels; it is invariably by means of brake shoes pressing on one side only.

The accommodation of the battery is also a problem with considerable difficulties. The larger sizes may weigh up to 4 tons, and the battery must be changed once per shift, or even twice per shift, if the duty is severe. The battery container may be provided with lifting eyes, as in Fig. 4, or wheels which run on angles set transversely, as in Fig. 6. The former method is satisfactory for small batteries, but 3 or 4 tons is a heavy load to handle quickly with a hand block or winch (power cranes are not always easy to provide in an underground garage).

It is well known that a particularly awkward problem on small locomotives is the disposal of the air reservoirs, which usually take the form of two or three cylinders of sizes convenient for the spaces available. On occasion the consequent layout of the brake piping is also made more difficult. An attractive design which has recently been evolved is shown in Fig. 8, from which it will be noted that three reservoirs have been built into a single unit. The combined battery/pantograph locomotive shown in Fig. 6 includes a combined unit of this type mounted at the back of one of the cab plates.

(6) DIESEL ENGINE

The market for underground locomotives is obviously fairly closely restricted, so that, whilst it is big enough for locomotive builders to design and develop special types of locomotive, it is much too small for Diesel-engine manufacturers to do the same with engines. Consequently the locomotive firms interested have selected those engines already in manufacture which appeared most suitable. Occasionally some special feature has been introduced or some limited modification made, but this is the maximum that has been possible. The selection of engines is primarily the locomotive builder's responsibility, and the main features of those used, since the first underground Diesel locomotives were approved in 1939, are summarized in Table 1.

All these engines are 4-stroke in-line units of two to six cylinders, developing up to 17 h.p. per cylinder and with running speeds of 1 100–1 700 r.p.m. Practically all use direct injection Whilst the piston speeds and power loadings are modest enough, such operating data as it has been possible to gather so far, suggest that, for the conditions in a mine, lower rather than higher figures are desirable; in a number of instances engine ratings have been reduced by fixing lower maximum speeds.

The locomotive power/weight ratio varies somewhat, but usually it falls between 6 and 7, which is fairly normal for the general type and class of locomotive.

It will have been noted from Section 2.2 that special precautions must be taken to deal with the consequences of the high temperatures of combustion, and with the toxic elements in the exhaust gas. The former hazard is dealt with in a variety of ways, but those engines, e.g. the Ruston series, which employ water-cooled manifolds, have an initial advantage. The maximum permissible quantities of carbon monoxide and the oxides of nitrogen (two parts and one part in a thousand, respectively) are very small, and good combustion in the cylinder is obviously necessary, although there is little difficulty in keeping within the statutory limits.

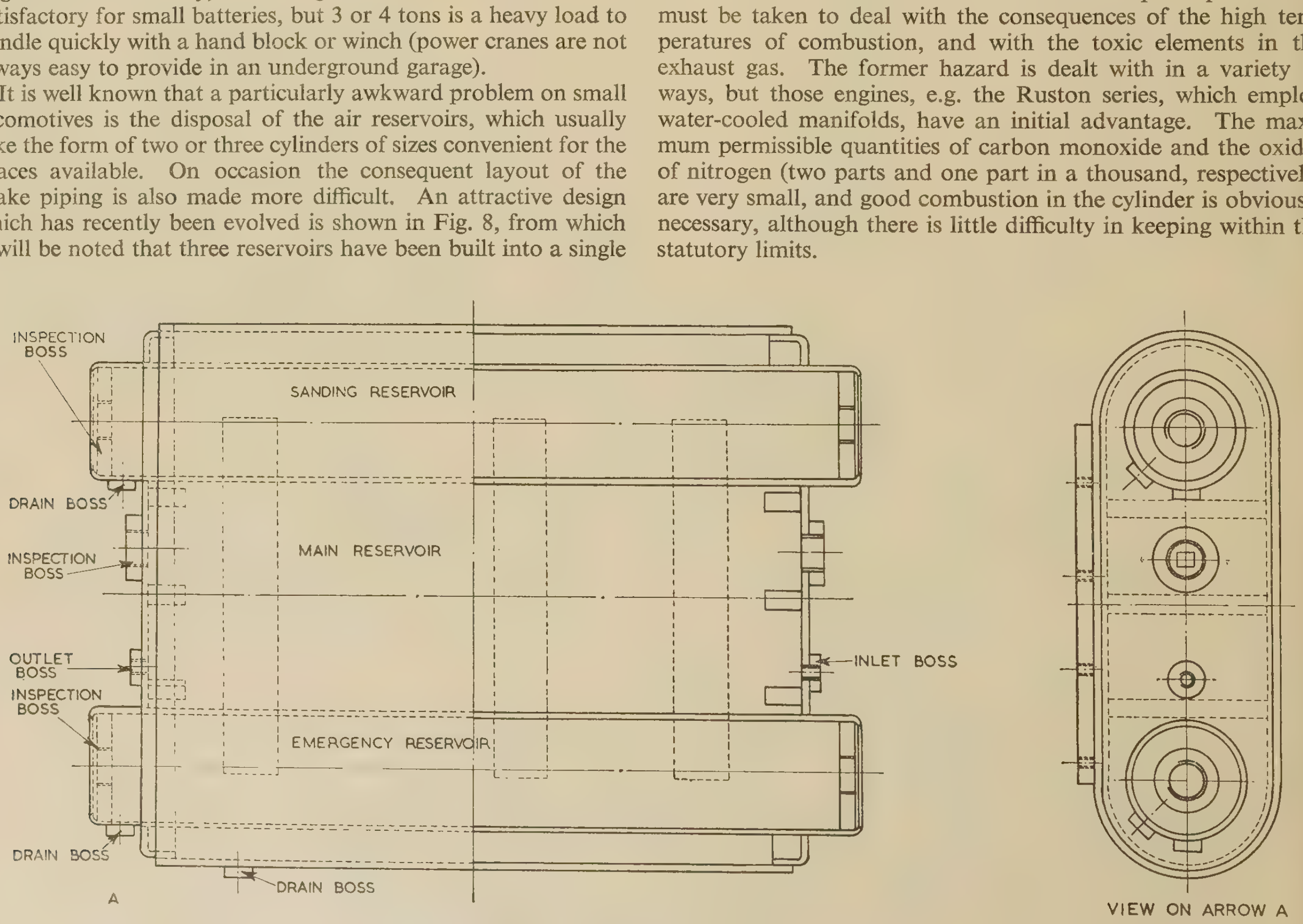


Fig. 8.—Combined air reservoirs.

Table 1

UNDERGROUND DIESEL LOCOMOTIVES
PARTICULARS OF DIESEL ENGINES

Engine builder	Engine type	Engine rating	Locomotive weight	Locomotive power-to-weight ratio	Number of cylinders	Cylinder size: Bore	Cylinder size: Stroke	Piston speed	Engine power-to-weight ratio
			tons	h.p./ton		in	in	ft/min	h.p./litre
Gardner ..	2 L 2	25 h.p. at 1 300 r.p.m.	4·75	4·25	2	4·25	6	1 300	8·95
	4 L 2	50 h.p. at 1 300 r.p.m.	7–8½	7·15–5·9	4	4·25	6	1 300	8·95
	3 L W	45 h.p. at 1 700 r.p.m.	5	9	3	4·25	6	1 700	10·7
	4 L W	65 h.p. at 1 700 r.p.m.	10	6·5	4	4·25	6	1 700	11·6
	6 L W	100 h.p. at 1 700 r.p.m.	15	6·7	6	4·25	6	1 700	11·9
Ruston ..	2VSHL	18 h.p. at 1 200 r.p.m.	3·5	5·15	2	4·5	4·5	900	7·64
	3VSHL	27·5 h.p. at 1 200 r.p.m.	4·5	6·1	3	4·5	4·5	900	7·76
	3VRHL	36 h.p. at 1 200 r.p.m.	6	6	3	4·5	5·5	1 100	8·32
	4VRHL	44 h.p. at 1 100 r.p.m.	7	6·3	4	4·5	5·5	1 010	7·65
	6VRHL	100 h.p. at 1 500 r.p.m.	15	6·7	6	4·5	5·5	1 370	11·58
	4YEF	75 h.p. at 1 500 r.p.m.	10	7·5	4	5	5·87	1 470	9·88
Meadows ..	4DT420	70 h.p. at 1 700 r.p.m.	10	7	4	5·12	5·12	1 450	10·3
Paxman ..	RQE	100 h.p. at 1 250 r.p.m.	15	6·7	6	5	5·87	1 230	8·76
Crossley ..	CWL.5	100 h.p. at 1 250 r.p.m.	15	6·7	5	5	6·25	1 300	9·88

(7) ELECTRICAL EQUIPMENT (EXCLUDING BATTERY)

Most of the manufacturing concerns now supplying battery or trolley locomotives for the mines have long been engaged in similar activities for surface traction. The principal obstacle to be negotiated was the development or adaptation of motors and control equipment to meet flameproof requirements. Considering the limited market, a good range of equipment is now available.

(7.1) Traction Motors

The narrow track gauges, and the small-diameter wheels of mining locomotives, constitute a very severe initial space restriction, but to this must be added the effect of that statutory requirement that the enclosure of the motor must be flameproof, which, of course, results in an increase in overall size. For the smallest of the recommended gauges (2 ft 0 in) a maximum of about 1 ft 9½ in is available for the traction motor and gear wheel, which is quite inadequate if the motor rating is to be high enough for the duty demanded of a 13-ton locomotive.

One consequence is the design shown in Fig. 9, in which most of the space between the wheels is occupied by a double-reduction gearbox, with the motor bolted to the latter and carried at the opposite side on the usual type of nose suspension. The motor is thus freed from the limitation of the track gauge and instead may be disposed so as to take advantage of the width between the frame plates. The motor shown in Fig. 9 is rated at 32 h.p., 1 450 lb tractive effort, 7·75 m.p.h. on 220 volts for one hour.

The pleadings of motor designers over the years, for the adoption of wider track gauges, are being met by the increasing proportion of haulage schemes using 3 ft 0 in; the cost of driving roads of sufficient size for these wide tracks is high and has already been noted in Section 1.

The motors are invariably provided with a simple 4-pole field system, and wave-wound roller-bearing armatures.

The bad track inseparable from mine roads has already been emphasized, and a recent development of a carbon brush fitted with a Neoprene pad, intended for use under conditions of severe mechanical shock, seemed worth investigation. Some brushes of this type are now undergoing trials in a Scottish mine.

Plans are now in hand for an intensive investigation into the performance of the motors on battery locomotives. However, there is as yet no evidence of motor temperatures anywhere near the limits, and so presumably the ratings are adequate.

(7.2) Control Equipment

A similar process of adaptation was necessary here. Controllers, resistors and other equipment developed for surface work were enclosed in flameproof boxes, and, restricted to the simplest types of circuits, proved a useful addition to mining equipment. As might be expected the resistors are one of the most difficult items, the interaction of flameproof enclosure and rating combined with the severe space restriction and the absence of any reliable operating data presenting the designers with a particularly awkward problem.

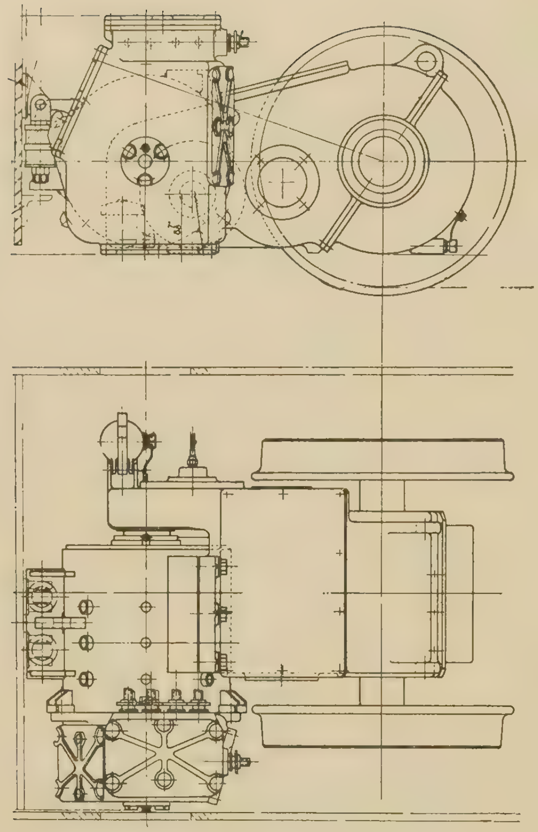
The rule of simplicity has operated here. The factor of limited space and the necessity of having to obtain fresh certification of every alteration tend to restrict the control schemes to simple series-parallel arrangements, and it is only in recent years, with the introduction of bigger and more powerful locomotives, that more complicated arrangements have been adopted.

(8) BATTERY

The economics of underground battery locomotives turn very largely on battery performance and cost. A marked improvement in either of these two factors would strengthen the claims of the battery units, and much consideration is being given to this problem.

(8.1) Battery Container

The battery is housed in a sheet-steel container, which in some designs has been subdivided into two or four sections. The regulations require all cell connections to be burnt on; bolted connections are not acceptable. When a cell is to be replaced



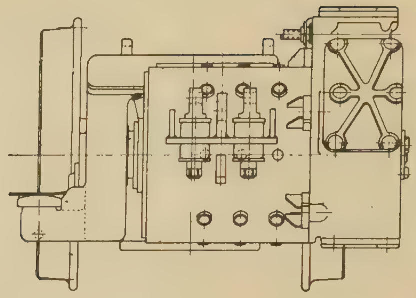


Fig. 9.—Traction motor with double reduction gears.

the burning of the connections necessitates elaborate safety precautions being taken, which could be avoided if the complete battery could conveniently be brought to the surface. The large single-container batteries are too heavy for this, and consequently the design shown in Fig. 10 was evolved. The main container is divided into four subcontainers, each complete with a set of burnt-up cells, and with the interconnections brought out to a flameproof connecting box as shown. It is a comparatively simple matter to disconnect a subcontainer, and it is light enough to be transported to the surface, where any necessary work can be done without restriction.

(8.2) Battery Types

The lead-acid and alkaline types are both practicable if the latter are restricted to the nickel–iron and nickel–cadmium varieties. More recent developments offer no immediate attraction because of high cost and short life. Actually, only the lead-acid type is in use underground; regulations are being drafted to establish safe conditions for nickel–iron cells.

(8.2.1) Lead-acid Batteries.

Lead-acid batteries are expensive and comparatively short-lived. They are guaranteed by the makers for 4 years or 1 250 cycles of charge and discharge, whichever is the shorter, and these figures determine in a large measure the economy of their use. A few batteries, operating on comparatively light duties, last well beyond the four-year period, but, in general, the life is 4–4½ years, so that the present guarantee appears to be the maximum possible.

(8.2.2) Battery Capacity.

Since battery dimensions are so severely limited the time/capacity characteristic is of critical importance. The general shape, given in Fig. 11, shows the heavy reduction in available capacity with increase in the rate of discharge, and since many mine roads follow an undulating path, heavy current discharges can form an excessive drain. At this stage of development, therefore, an empirical working rule might be stated as follows: if the duty consists of long hauls with heavy loads against

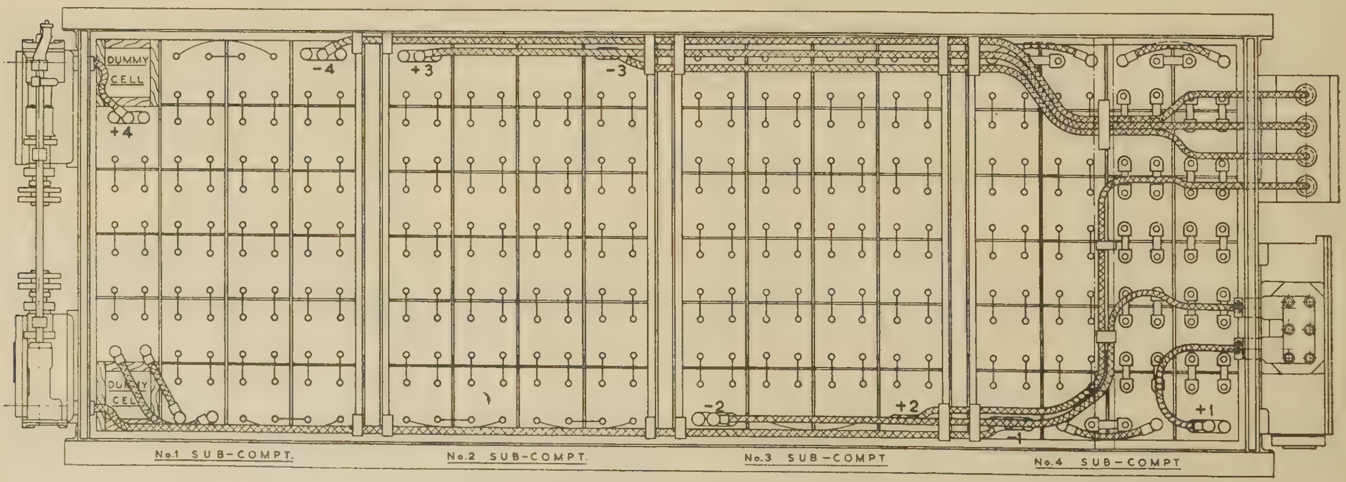


Fig. 10.—Mining-locomotive battery in four subcontainers.

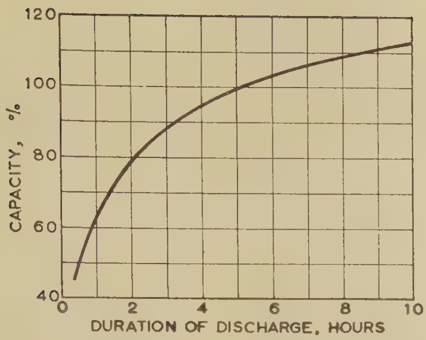


Fig. 11.—Time/capacity curve of lead-acid battery.

gradients in excess of about 1 in 60 the present designs of battery locomotive will be found unequal to the job.*

(8.3) Battery-Charging Equipment

An installation of battery locomotives underground must include some provision for recharging, and this should obviously be as simple and foolproof as possible. Several types of equipment have been developed and have proved satisfactory. Since the power supply to the charging station is invariably alternating current, a suitable transformer and a.c. switchgear are common to all. The variation is in the method of rectification and the control of the charging current.

One manufacturer uses a selenium rectifier, designed to give a taper charge to the battery. A relay operates when the gassing stage is reached, and charging is terminated after a preset time. In another case, a mercury-arc-rectifier bulb type of equipment is used. A third manufacturer uses excitron tubes providing a taper charge; in this case also, when the gassing stage is reached, a relay is operated which causes a reduction in voltage, and charging is concluded at a reduced rate for a predetermined period. The resulting charging characteristic for a 94-cell 420 Ah battery—one of the largest sizes in use—is given in Fig. 12.

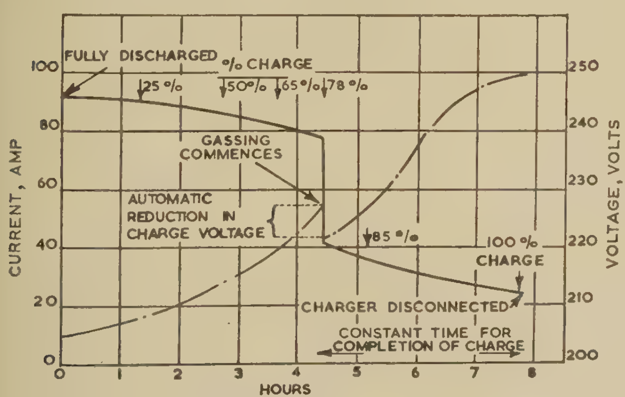


Fig. 12.—Automatic charging characteristic of 94-cell 420 Ah battery.
——— Current.
– – – Voltage.

(8.4) Battery-Changing Equipment

Since a battery often needs replacing every half shift and rarely lasts longer than a shift, the method of changing batteries is of considerable importance. In the broadest terms, it can be done either by lifting or rolling; either method is satisfactory with the

* It is well understood that 'long hauls' and 'heavy duty' are relative, not absolute terms, but they are the best available at present and their interpretation is entirely a matter of experience.

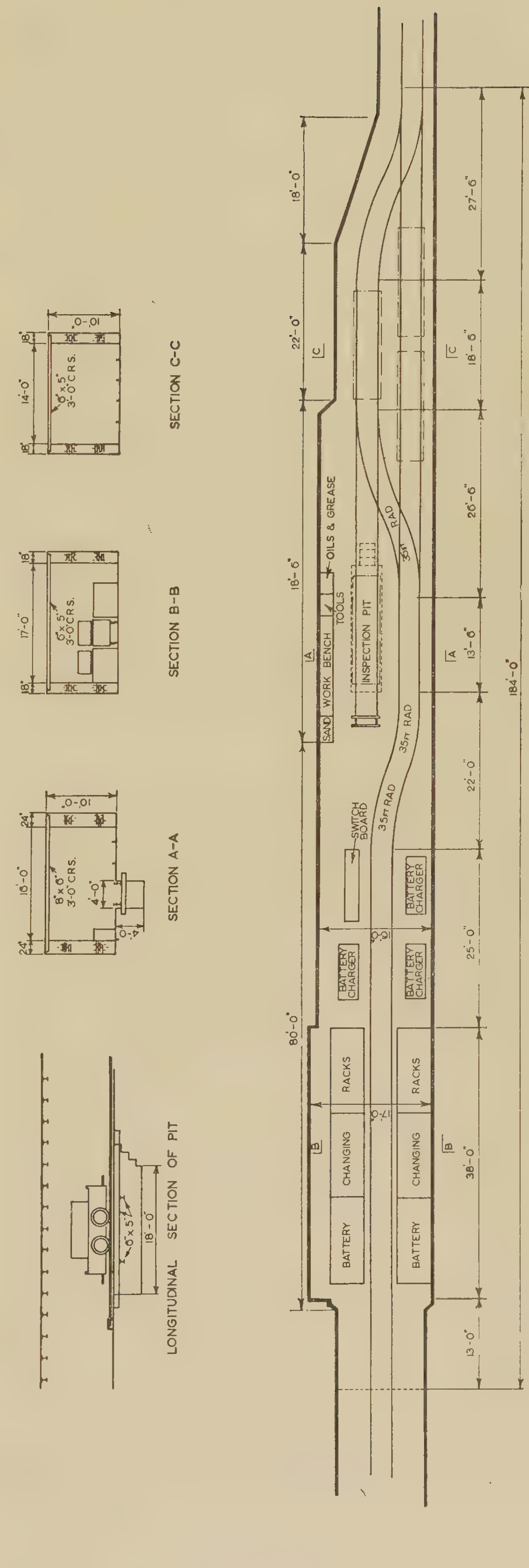


Fig. 13.—Underground garage for three battery locomotives.

smaller units, but the 13-ton locomotives which are being used in increasing numbers have batteries weighing four tons. This is a more difficult problem, particularly in the limited space of an underground garage. Hoisting tackle can be, and is, used, but traversing with four tons 'on the end of a rope' demands much care. Consequently the alternative of 'rolling off' has often been preferred. In this case the battery containers are provided with four wheels, arranged to roll on angles or strips placed transversely across the locomotive frame. The batteries can then be moved from the locomotive on to a frame, either manually or by means of a small motor.

Since it is undesirable for the four tons weight to be permanently supported on the roller bearings of the wheels, the spindle centres are displaced so that the battery can be pushed on or off the bearings as necessary.

A garage layout providing the necessary facilities is no easy problem, but a good design for three locomotives is shown in Fig. 13. The essential principle, which has been widely adopted, is to run the locomotive track between two banks of changing racks, as shown in the plan and at section B–B. The discharged battery on the locomotive and the charged one on the rack are then linked together, and it is a comparatively simple matter to move the two together, the discharged battery on to the empty rack and the charged one on to the locomotive—an operation which can be done manually or by means of a small motor. A severe drawback is the inaccessibility of the batteries in this position, and in particular, of the charging plugs and sockets if these are on the side next to the charged battery.

It will be noted that equipment is placed end-to-end, so that the width of the garage may be kept to a minimum; the 17 ft width is reduced to 16 ft immediately outside the section accommodating the changing racks. The result is a length of 184 ft; for a fleet of six locomotives this would be nearly doubled.

(9) POWER-TRANSMISSION EQUIPMENT

Whatever the type of locomotive, equipment must be provided to transmit power from the Diesel engine or traction motors to the road wheels. In the restricted space available this has presented an interesting and difficult problem to the designers.

In the case of Diesel locomotives a simple gearbox has obvious attractions and has been used in a number of designs. The desire for a more flexible link has led to the introduction of one of the simple types of hydraulic coupling, and a large number of locomotives are in service with some form of this gear. The N.C.B. has a small number of Diesel locomotives with Voith torque convertors and one with a Salerni-type torque convertor, but the use of these has not, as yet, found wide favour. It is difficult to make any true comparison between a gearbox and a fluid coupling. When such attempts have been made, the issue has invariably been obscured by other matters, usually related to the local conditions of operation. Out of all the conflicting factors only one has tended to assume positive importance, namely that the fluid coupling lacks the braking effect possessed by a gearbox.

In the case of an electric battery or trolley locomotive, a wider variety of designs have been developed. Apart from the standard single-reduction spur gearing, which is widely used, the low operating speeds have facilitated a design of motor using two stages of speed reduction; that design, with the motor mounted on and supported by the gearbox (see Fig. 9), has already been noted. Space restrictions led one manufacturer, with commendable energy, to develop and offer the three alternatives of straight spur gears, worm gears and bevel gears.

All these variations on a common theme have proved more or less successful.

(10) PNEUMATIC EQUIPMENT

All locomotives must be equipped with a mechanical hand brake, and most have either air or electric brakes in addition. With the lighter units the issue is not very critical, but above 7 or 8 tons, powerful and effective brakes are vital.

For Diesel locomotives the choice of air brakes is an obvious one, and once again the equipment is kept to the simplest possible form. Standard types of reciprocating compressor belt driven from the engine and delivering air at about 80–100 lb/in², with straight and emergency applications, cover the majority of designs. Some trials have been carried out on one type of locomotive with both air-cooled and water-cooled compressors at 150 and 300 lb/in²; so far, the water-cooled type at 150 lb/in² has proved the more suitable for mining conditions.

With electric-battery and pantograph locomotives the obvious solution is to fit a motor-driven compressor which can be housed in any convenient position on the locomotive frame. If the locomotive is to be used in conjunction with man-riding cars, the air brakes are usually extended to operate on the cars, too; man-riding cars are subject to special regulations regarding brakes, and this is one of the most convenient ways of meeting them.

(11) AUXILIARY EQUIPMENT

It is not an uncommon experience in traction work to find that a large proportion of the operating difficulties and failures occur on the auxiliary equipment. Mining locomotives are no exception, for the regulations themselves necessitate the use of much additional apparatus designed to establish safe conditions of operation.

The inlet and outlet flametraps, of identical design, give little or no trouble. The outlet trap has to be changed every 24 hours, but a simple maintenance procedure is all that is necessary.

The exhaust conditioning system, which may comprise some or all of such items as water tanks with float mechanisms, water sprays, a long exhaust pipe and a conditioner box of widely varying design, is a different problem. Each manufacturer has developed, and where he has felt it useful, patented, his own system. The equipment occupies considerable space, it is costly, and it is difficult to maintain. It is designed to deal with high temperatures and corrosive elements, and considering the difficult nature of the problem, a very high degree of success has been achieved. Some of the more important operating experiences are discussed in Section 14.

Provision must also be made for connecting the battery (*a*) to the charging supply, and (*b*) to the traction motors on the locomotive. The plugs and sockets which are used for this purpose must be flameproof, and to ensure their safe manipulation, a suitable isolating switch must also be provided.

Simple as they would appear to be, the plugs and sockets have been the subject of much study. Since they must carry heavy currents—e.g. one design has a continuous rating of 170 amp at 250 volts—and be of flameproof construction, they cannot be small, and the manual handling of a plug weighing 20 or 30 lb, sometimes in a badly restricted space, is all against quick battery changing. Double- and single-pole plugs and sockets are in use; an example of the latter, made integral with the isolating switch, is shown in Fig. 14.

The necessity for mounting this equipment on the battery container itself has always presented an awkward problem; Figs. 4 and 6 illustrate this very clearly.

(12) BRAKING IN GENERAL

Whatever the type of locomotive, adequate braking power is a paramount requirement. The general statutory requirements are that loads and speeds must be safe. This has been extended,

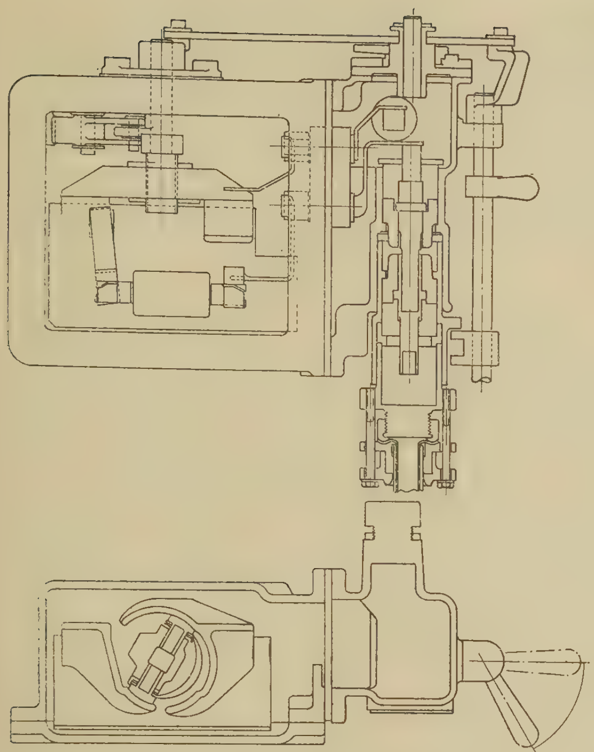


Fig. 14.—Coupling plug and socket integral with switch and fuse box.

in the case of the regulations established for the pantograph-locomotive installation at Sandhole Colliery, by the requirement that the minimum rate of deceleration of a locomotive and train shall be 0·2 m.p.h./sec. Whilst this has a specific application to the installation cited, there is always the possibility that it might be treated as a precedent and the regulation widely applied. The policy of the N.C.B. is to deal with each case on its merits, but in the great majority of instances, much greater braking power than this has been provided. There are a minority of cases where the rule has caused some difficulty.

Ways of stopping trains quickly and safely are continually occupying attention. The essence of the problem, as in all traction work, is to maintain the braking effort just below the locking point of shoe to wheel and the slipping point of wheel to rail, but in the widely varying conditions of a mine this is difficult to achieve. The maximum possible braking power is essential, but it has to be kept within two critical limits which may vary widely.

A general issue which is receiving much study is whether brakes should be on the locomotive only or on the mine cars as well. Man-riding cars must have certain braking provision, whatever the locomotive equipment may be. There are a few mine cars fitted with a simple form of parking brake, but in the great majority of cases the brakes on the locomotive have to stop the whole train. With increasing weights the braking power often approaches the maximum possible; indeed train weights may be limited to avoid this. But to fit mine cars with brakes, e.g. air brakes, which can be operated from the locomotive driving cab, raises a whole range of problems, of which the extra cost of the mine car is the least. For the present, at any rate, the search should be directed to more powerful and more efficient locomotive brakes.

A hand brake for parking purposes is required by law; other types which are in use or have been considered are compressed air, electric rheostatic, electric regenerative and electromagnetic.

(12.1) Compressed Air Brakes

All the larger locomotives of whatever type are equipped with compressed-air brakes as the main operating brake. The braking action is powerful, the equipment is not unduly complicated and it has a satisfactory record of service in the mines.

(12.2) Electric Rheostatic Braking

Confined to the larger sizes of electric locomotive, rheostatic braking is kept to the simplest possible terms. It is a useful form of brake but not as good as compressed air, because from its nature it provides little or no braking power at speeds below 4 or 5 m.p.h., which, as already mentioned, is a matter of great importance in a mine. It is desirable that the resistors should be as liberally rated as possible, so that the minimum of restriction need be imposed on the driver.

(12.3) Electric Regenerative Braking

Regenerative braking is always attractive in principle; the restrictions of working in a mine make any possibility of using it there doubly so. The steepness of many mine roads has already been mentioned, and the possibility of regenerative equipment being used on them has often been considered, but the cardinal principle of keeping equipment simple has always made its rejection necessary. The advantages of this form of braking would have to be very marked, and also obviously capable of realization, to justify the much more complicated equipment.

A pantograph-locomotive scheme would obviously offer the best scope, but at present none is in sight. There has been one instance, namely the new Hawthorn mine reconstruction in Durham, where extensive investigations were made into the possibility of regenerative battery locomotives. The disposition of the mine roads, as will have been noted from Fig. 2, provides considerable running down heavy gradients, and the possibility of reducing the drain on the battery by using the regenerated current for recharging purposes was attractive. Unfortunately, the charging process liberates hydrogen, and if a charging current is passed through a battery approaching full charge, the rate of liberation becomes very high. Since hydrogen is an explosive gas, subject, as already explained in Section 2.2 to strict safety regulations, the possibility had to be ruled out.

(12.4) Electromagnetic Braking

Electromagnetic braking has also been investigated. It starts with the inherent disadvantage that its effective operation must depend on restricting the variation of the air-gap to reasonably small limits—a difficult problem in the moving roads of a mine. Something can be done in this direction by using the shortest possible wheel base, but this brings other problems of overhang and lateral throw. If the locomotive is of the pantograph type, failure of the power supply means no current for the magnetic coils—the device 'fails to danger', thus transgressing a cardinal principle of all mining equipment. If it is applied to a battery locomotive, the current must be drawn from the battery, which is then additionally loaded, whilst it is often difficult enough to provide sufficient battery capacity for the normal haulage duty. In one case considered in some detail, the additional cost would have been about £1 000 per locomotive.

(13) COUPLINGS

Locomotives designed to haul heavy mine cars must be equipped with modern couplings. These may be, in some degree, automatic in operation, and if the cars are emptied by means of a tippler, they must be capable of the necessary swivelling action. Little is known, as yet, of the forces they must withstand, whilst

liability to uncoupling when operating over the uneven tracks underground is a hazard which must be closely watched. Any necessary manipulation should be possible without the operator having to introduce any part of his body between car ends.

The change in conditions is well illustrated by the fact that, whilst the General Locomotive Regulations of 1949 make no reference to coupling strength, some recent Special Regulations expressly state that this must be not less than twice the adhesive weight of the locomotive for tight-coupled trains and $2\frac{1}{2}$ times for slack-coupled ones.

(14) OPERATIONAL EXPERIENCE

With over 800 locomotives now at work underground, reliable operational experience is at last being collected.

(14.1) Battery Locomotives

The records of 30 years or more show nothing more serious than minor electrical faults, such as short-circuits and some mechanical damage to battery cells. The generation of hydrogen, always a potential danger, is closely watched, and any serious incident from this cause has been rare.

(14.2) Diesel Locomotives

The fact that a Diesel locomotive is a self-contained unit, capable of operation wherever there are rails, greatly eased its introduction into the mines. The conditions, however, are particularly severe for a precision-built prime mover like a Diesel engine, and a variety of severe operational difficulties have had to be overcome.

The toxic exhaust gases, discharged from the engine at a high temperature, must be rendered harmless before they can be allowed to pass into the ventilating air of the mine. They are usually passed through some form of water tank, but the problem of safely dissipating the heat has not been easily solved, and some fires, whilst localized and rapidly extinguished, served to emphasize the hazard.

In certain cases, corrosion of parts of the exhaust system has given serious trouble.

In total, a high standard of maintenance of the Diesel type is at once both much more difficult and more essential than for the battery locomotive.

(15) LIMITATIONS OF EXISTING DESIGNS

Statutory restrictions permit the use of pantograph locomotives on gradients up to 1 in 25, and the Diesel and battery types up to gradients of 1 in 15. However, since battery locomotives cannot be used on any gradient over about 1 in 60, the practical result is that, between level and 1 in 60, the field is shared by both these types, whilst on gradients steeper than this, Diesel locomotives only are used, except for one or two special pantograph locomotive schemes.

For all types of locomotive, braking is the most critical problem, and any advance in the art of stopping trains would be of immediate value. Hitherto all braking has been done on the locomotive only, but the introduction of mine cars weighing up to 10 tons gross, coupled with higher speeds of operation, is going to necessitate further consideration being given to power braking on the train. Apart from consequent difficulties, connected with the coupling and uncoupling operations, bigger compressors and more complicated braking equipment would have to be accommodated on the locomotive itself.

The exhaust-gas conditioning system of Diesel locomotives needs a fresh examination to see whether the problem of high temperatures and toxic elements can be more effectively solved. On the battery locomotive, an improvement in the battery time/capacity characteristics would be valuable, as would any modification of the electrical system which would lead to some form of continuous control. Accessibility for ease of maintenance is an ever-present problem which is particularly acute in the case of the Diesel locomotives.

One overall qualification must always have first place: such improvements must not nullify the simple robust character inherent in all good mining equipment.

(16) HIGH-SPEED REMOTE-CONTROLLED TRAINS

It is always dangerous to prophesy, and in the case of mining locomotives the future is particularly indefinite, but important developments lie ahead. For 100 years, first ponies and then haulage engines dragged small trains of tubs at speeds of 2–3 m.p.h., and even now, with the advent of locomotives of modern design, a great deal of running is done at less than 10 m.p.h. For the conditions which lie immediately ahead—highly-mechanized faces producing large tonnages of coal at ever-increasing distances from the shafts—a radical improvement is necessary, and instead of haulage at 10 m.p.h., speeds of 30–40 m.p.h. should be envisaged.

This can be achieved only by fundamental changes in the operating conditions. Locomotive speeds are restricted on the grounds of safety. If, instead of running trains along the main haulage roads where personnel must also move and work, special roads were driven for transport only, the problem would be different. If a second intake road could be provided, for traction purposes this could be made of comparatively small diameter, say 6 or 8 ft. (Other considerations, e.g. the amount of ventilating air, might dictate a larger road than this.) If the rails were laid on segments carried on the road rings, trains could safely be operated at these higher speeds without danger to life. The rings and segments could be designed to make maintenance easy, so that the track could be maintained at the standard of alignment necessary for these speeds. Electric pantograph locomotives would serve admirably as the form of motive power and could be operated by remote control, thus saving the cost of drivers. Practically all the traction problems involved are familiar ones and would present no difficulty in solution.

An alternative might be the development of a suspended monorail system, which again could be confined to special haulage roads and would have the very notable advantage of eliminating all problems associated with track maintenance. A slight movement of the suspension rail due to roof movement would have little or no effect on the running of the cars.

Since an essential condition of this type of haulage system would be the exclusion from the road of all personnel whilst trains were running, an improved standard of safety should also result.

(17) CONCLUSIONS

Ten years of intensive and successful development have produced Diesel and electric locomotives well suited for the work they have to do, although, owing to the physical conditions and safety regulations, none is free from some serious limitation. Consequently, whilst as an immediate policy every possible method of improving existing designs should be investigated, due consideration must be given to any new development which offers possibilities of more efficient and safer haulage. In particular, where the conditions are suitable, a radical approach to the whole problem is necessary. The solution might lie in trains operated by remote control, running in special roads at a speed of 30–40 m.p.h.

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DISCUSSION BEFORE THE UTILIZATION SECTION, 15TH MAY, 1956

Mr. A. E. Crook: The author gives a good picture of locomotive practice in British coal mines and shows that the rate of application is still increasing. Enormous changes and progress have been made in our haulage practice since the 1945 report of the Technical Advisory Committee on Coal Mining, popularly known as the Reid Report, pointed out the advantages of locomotives where conditions are suitable. That really meant a method of mining with nearly level roads, i.e. horizon mining.

Our experience of underground transport by locomotives during the last decade has shown its outstanding advantages both for production and safety, and has fully justified the recommendations made for its adoption. This is not surprising in view of the very successful use of locomotives in the coal mines of America, France, Belgium, Holland and Western Germany. In the latter country, for instance, at the end of 1952 there were over 4300 locomotives of which 36% were driven by compressed air and used on main and subsidiary roads; 29% were of the electric-trolley type and used on main roads only; 18% were of the electric-battery type and 17% were Diesel driven, both of which types were used on subsidiary and main roads. These figures may give some indication of the potential use of locomotives in our mines, whose annual output of coal is about twice that of Western Germany.

The adoption of horizon mining in many of the new mines will provide main haulage roads that are very stable and suitable for high-speed transport by locomotives, i.e. speeds of say 15 m.p.h., which may be sufficient for distances of up to 4 miles. The speeds of 30–40 m.p.h. envisaged by the author seem to be unnecessary and unobtainable, having regard to practicable rates of acceleration and deceleration, to unbraked mine cars and to the distance run.

The higher the speed the greater is the braking problem, and consequently the smaller the trailing load with unbraked mine cars. The problem can be solved by using cars with power-operated brakes that can be applied by the driver whilst the train is in motion. This system is being adopted by some of our ironstone mines, where it is considered that its advantages outweigh the disadvantages of making special arrangements for dealing with the cars at loading and unloading points when they are uncoupled from the train. Moreover, the system ensures that any part of a train which becomes detached is automatically brought to rest by the application of the emergency brakes. This system of braking is also being used for special man-riding trains in many of our coal mines.

I strongly support the author's comments on locomotive cabs and would urge that all new designs should provide for the proper accommodation of two persons in any cab, and that there should be two driving positions unless one driving position will allow the driver to have a clear view of the road ahead without leaning out of the locomotive no matter in which direction it is travelling.

I cannot support the author's view that special regulations act as a powerful deterrent to the installation of new types of locomotives, and presumably of other machines. Special regulations governed the use of more than 200 locomotives before the Coal Mines (Locomotives) General Regulations were made in 1949. They were the basis for those general regulations, and thus they could not have been restrictive having regard to the rate of increase of locomotives since that time. Moreover, a large number of single- and multi-rope friction winders with both manual and semi-automatic control are being installed under agreed special regulations, which again show that this type of regulation does not restrict development but promotes it. Nevertheless, I should be glad if the author would state in what way special regulations act as a powerful deterrent.

The electric-gyro locomotive may be classed as a mechanical-battery locomotive, and it may be most suitable for small duties in subsidiary haulage roads where means of re-energizing the flywheel at the outbye end of the road are provided. Would the author give his views on the field of application of this locomotive and also on that of the robust compressed-air locomotive used so extensively in Europe?

The Diesel locomotive has played probably the most important part in the adoption of locomotive transport in our mines. However, it produces some noxious gases which have to be conditioned, and more than twice the heat caused by the electric trolley locomotive on the same duty. Although the exhaust conditioning equipment has been quite successful, I support the author's suggestion for a fresh examination of the problem. On page 40 of 'A Brief Review of Science and Technology in Western Germany'* there is a description of a special attachment for Diesel-motor exhaust pipes. This is said to convert the exhaust gases into carbon dioxide and water vapour by catalysis; 90% of the carbon monoxide and 85% of the hydrocarbons are said to be made ineffective in this way. This attachment seems to be worthy of investigation both for Diesel locomotives in mines and Diesel engines in vehicles in our cities and towns.

In view of the pitching of locomotives and any consequent uncoupling hazard, would the author give his views on longer wheel bases for main-road locomotives and on the possibility of using small shunting locomotives for negotiating any curves of small radii at the terminal stations?

Mr. H. Newsam: In Section 7.1 the author suggests that there is some difficulty, in the case of the 2 ft gauge, of obtaining an

* D.S.I.R.: 'A Brief Review of Science and Technology in Western Germany' (H.M. Stationery Office).

adequate rating from a motor with single-reduction gearing; but the motor used on the locomotive shown in Fig. 4 is of the single-reduction type and has a one-hour rating of 45 h.p. 2000 lb tractive effort at 8·6 m.p.h., which is greater than the rating of the double-reduction motor referred to in the same Section.

Single-reduction axle-hung motors have been built for mine locomotives of 500 mm (19·7 in) gauge. These motors are specially constructed with short armature end windings at both ends. The motor for the locomotive shown in Fig. 4 has a short end winding at the driving end only, and a sectional view of this motor is shown in Fig. A.

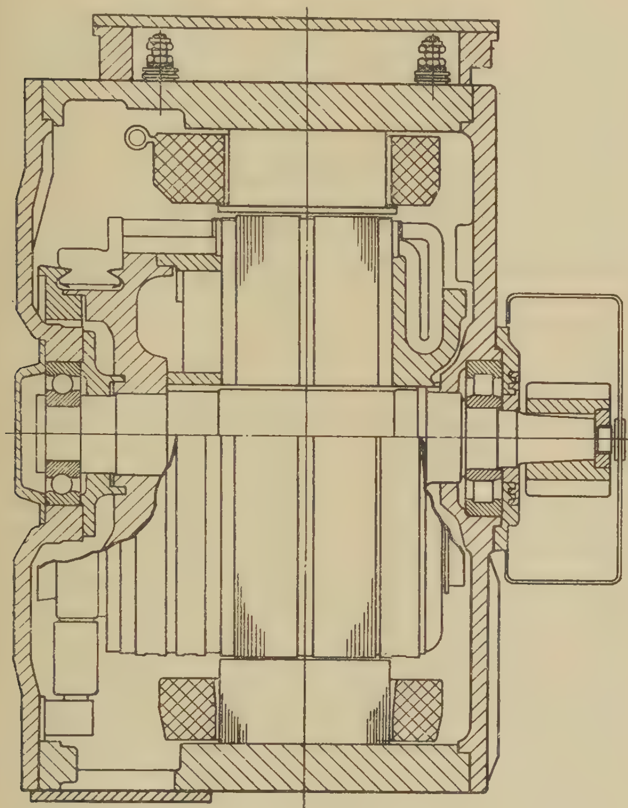

Fig. A

For another locomotive for a British mine, a motor similar to the one illustrated has been developed, having a special design of pinion with the teeth cut in a stub shaft which is a press fit in the end of the motor shaft. With this construction it is possible to get a relatively high gear ratio of approximately 7 : 1.

An alternative type of double-reduction motor which has been used successfully in British mines is an American design modified to meet British mine regulations and built in this country. In this case the gear-box is made as an integral part of the motor frame.

It is stated in Section 3 that the heavier gradients are invariably against the full train. Perhaps the author could explain why this should always be the case.

Mr. C. D. Wilkinson: There may be some disappointment that, of the 800 locomotives in use underground in this country, over 75% are Diesel driven, and that there is only one trolley-locomotive installation. The fact that trolley locomotives have not been more widely adopted does not stem from lack of interest or doubts as to their capabilities, but rather from economic factors which are to a certain extent influenced by the special regulations governing their use. The general regulations which govern the use of battery and Diesel locomotives have worked well, and, as can be seen from the figures, have fostered the use of this type of plant.

The permitted voltage for trolley locomotives is only 250 volts d.c., so that the percentage voltage drop under working conditions is very large and often makes a trolley scheme uneconomic. It might be argued that a 500-volt system could be used with the mid-voltage point earthed, but the width of the pantograph bow called for in the regulations is such that a double pantograph is impracticable in underground roadways. In Germany the regulations permit progressive increases in system voltage as the height of the trolley wire is increased, with a maximum system voltage of 850 volts and a maximum working voltage of 750 volts, the difference presumably being an allowance for over-compounding. There is no doubt that voltages of this order would materially affect the economics of a mining trolley-locomotive system in this country.

There is considerable difference of opinion as to the most suitable gauge for underground locomotives, and whilst gauges of 3 ft 6 in and 3 ft are admirable from the point of view of stability, they often lead to the retention of two different gauges in one mine, because trams of such broad gauge can seldom be used for the transport of materials alongside the conveyers in the secondary roadways near the coal face. I suggest that a gauge of 2 ft 6 in will meet all conditions.

Mr. G. Smith: One striking fact is the remarkably small number of battery locomotives in relation to Diesel locomotives at the end of 1955. This is surely a challenge to those concerned with the development of electrical transmissions for locomotives of this type. Bearing in mind the essential need for simplicity of design, and from this naturally follows ease of maintenance, surely the battery locomotive embodies these requirements.

My remarks are therefore concerned principally with locomotives having electrical transmissions, and I should be interested to know the overall gear ratio of the motor unit shown in Fig. 9. I should also like to know to what extent motors with right-angle drives have been employed, enabling the very highest possible gear ratio to be used.

In Section 8.2.1 it is stated that the life of lead-acid batteries is 4–4½ years. Does this take into account the modern developments which have been made in separators? In other words, have batteries incorporating these modern separators been in use sufficiently long for the present-day battery life to be truly assessed?

It is noted that, where the gradient resistance is about 37 lb/ton, the battery locomotive appears to be unequal to the job. I should like to know how this resistance compares with that of the rolling resistance of the trailing load of present-day track and mine cars, and to what extent this may be expected to be reduced with the improved track and possible developments of mine cars in the future, resulting in reduced current demand on the battery. I should also be interested to have a comparison of the initial cost of, say, a 90 h.p. 13-ton battery locomotive with that of the 100 h.p. 15-ton Diesel locomotive.

Some ten years ago I was associated with the production of a number of shuttle cars, and whilst these were battery-operated vehicles and do not really come within the scope of the paper, I should like to know whether this form of underground transportation has proved successful or not.

Mr. J. Beasley: In a paper of this nature it is obviously very difficult for the author to cover every aspect, but as he has made some reference in Section 7.2 to the difficulties experienced with resistors, I feel that he should have made some reference to the relationship between the resistor and the effective use of the battery.

To make this point clear I quote figures relating to the locomotive illustrated in Fig. 4. On that locomotive the resistor is contained in a tank, capable of dissipating a load of 2·2 kW with a case temperature rise of 100° C. If the locomotive operates for 5 hours, using the resistor at its continuous rating, a total energy of 11 kWh is dissipated. As a 200-volt 420 Ah battery is fitted, having a total energy of 84 kWh, the resistor energy is therefore 13% of the total. When the locomotive was first put into service the resistor failed, and as it takes about 5 hours to reach maximum temperature at the normal rating, this suggests that the energy being wasted in the resistor was, at least, of the order of 13%. Consequently it is far more important to provide a form of control involving the minimum amount of resistance loss than to design resistors capable of dissipating greater energies without failure.

The locomotive in Fig. 4 was modified so that the two halves of the battery are connected in parallel for starting and slow-speed running, and subsequently there has been no resistance failure, indicating that amount of power wasted has been reduced.

Similar considerations apply to the compressor, which, if run at its continuous rating, could also use about 13% of the energy on a 5-hour basis. The author's suggestion to fit continuous brakes to mine cars would increase the battery power required for this purpose and reduce that available for traction.

Some interesting information would be obtained if tests were made at the National Coal Board's new testing station to determine what percentage of the battery power is, in fact, utilized for traction.

Mr. J. A. C. King: It appears that many of the problems associated with braking would be immediately solved if we imported an idea which the aircraft and petroleum industries have been using for quite a while, namely the self-sealing hose coupling unit. If this could be made automatic and incorporated in the train coupling mechanism on the centre line, we could then swing cars round on the tippler, and it would not be necessary to walk into the space between wagons. The cars would be pushed together and held until released. A certain amount of redesign would be involved, and it would be necessary to stiffen the component parts of the automatic hose couplings, but basically I think that it is sound, and all the associated problems of train braking so far mentioned would be solved.

Many of the problems, particularly those associated with gradients, might be more easily overcome if we thought more in terms of powered cars at intervals throughout the train.

Could the author give some indication of what is involved in handling the cars into and out of the lift in the shaft when they have air brakes or vacuum brakes? Obviously, not only must the brake fail to safety if there is an accident to the train in the haulage way, but we have to overcome that very provision of failure to safety in order to move enough cars into or out of the cage. The skip method of hoisting to overcome that would appear to require more handling on the surface.

There have been several comments on lead-acid batteries, but what is the effect of using nickel–iron or similar batteries on these locomotives?

Mr. P. N. Butler: In Section 8.3 the author mentions both taper and 2-step taper battery chargers. The characteristic of the latter is shown in Fig. 12. It would be interesting to know which type of characteristic the author prefers when charging batteries of the capacity mentioned.

In Section 12 the author states that the braking rate for the trial trolley-locomotive installation at Sandhole colliery is 0·2 m.p.h./sec, but the text of the Special Regulations refers to time and not to distance. In the following two examples the average rate of deceleration as a function of speed and time is the same, whilst the distance travelled is different.

In Fig. B the rate of deceleration at the start of braking is very low, but increases very rapidly when the speed is approaching zero, whilst with Fig. C the reverse is the case. A high rate

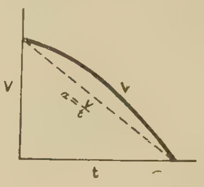

Fig. B

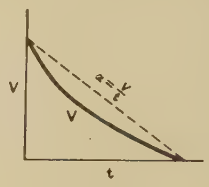

Fig. C

of deceleration occurs at the start of the braking period, subsequently reducing, so that the time to come to rest is the same as in Fig. B. Since the integral of time and speed is distance, it is evident that the distance travelled is different. I consider, therefore, that it is incorrect to specify a deceleration rate for braking, since surely it is the stopping distance rather than the stopping time with which one is concerned.

In Section 12.3 the author deals with regeneration and the possibility of using this type of braking with trolley locomotives where presumably its adoption would be to reduce brake-block wear when running on steep gradients, although possibly the author has in mind the saving of energy consumption. I am of the opinion that regeneration could be provided easily by using compound-wound motors, but it would be necessary to ensure that a receptive line was available. My experience is that this would not be the case for the greater part of the day; therefore it would be necessary to provide static equipment in the substations to absorb the energy returned to the line during regeneration.

In Table 1 the author gives the ratio of horse-power per ton of locomotive weight for Diesel locomotives. For comparative purposes similar figures for battery locomotives would be interesting. These figures are a ratio of battery weight to gross locomotive weight and battery energy per ton of locomotive weight.

Mr. L. S. Laycock: The author refers to the larger locomotives being provided with a driving cab at each end because it is necessary to have unobstructed vision from the driving position, and at the same time such an arrangement provides a seat for a second person to use whilst travelling on the locomotive. Would the author indicate what he considers to be a safe vision distance, because there are many of the larger battery locomotives in operation which have only one cab? Running speeds are invariably such that the locomotive could not be brought to rest in a distance less than 200 ft, the minimum length of the headlamp beam, and provided that the driver can see the full roadway for the greater part of this distance from a cab at the rear, is a second cab really essential? Furthermore, the provision of a second cab means additional equipment, in the form of a second set of controls, which increases the initial cost of the locomotive. With regard to the use of the rear cab as a second seat, should this be permitted for specially authorized personnel, is it not possible that it would also be used by unauthorized persons, who would be out of control of the driver and liable to operate some of the controls such as coupling release gear, etc., and thus partially take control of the train from the driver?

The flywheel of the gyro-locomotive is usually installed in a hydrogen-filled casing. Could the author indicate the reactions of the Ministry of Fuel and Power safety inspectors to the use of such a design below ground, and does he know whether their use would be subject to special regulations?

Is the higher rate of installation of the Diesel locomotives over the battery type due to financial considerations, or because

the engineering staffs who are responsible for making the decisions are more mechanically than electrically minded?

Mr. F. G. Hathaway: I am rather disappointed that the author makes no reference to the consideration of a properly designed mine traffic control system, because the more locomotive haulage is considered, the more advantage has to be taken of such a system, which can do a great deal to increase safety and to speed the train rate, particularly in the vicinity of the shaft at the pit bottom.

Properly located signals forming part of a traffic control system would avoid a number of accidents which might occur during shunting operations. At the pit bottom a number of personnel can be eliminated by concentrating all the operation of signals and points into one control point. Furthermore, the capacity of a single line between the face and the shaft can be increased by the installation of a traffic control system.

Mr. J. Cowan (*communicated*): As the Regulations pertaining to locomotives underground have been established following discussions between the Ministry and the National Coal Board, the author's criticism is rather difficult to understand. So far as I know, the N.C.B. has not discussed with the Inspectorate proposals to use battery-trolley, e.g. Fig. 6, or trolley-reel locomotives. There has been no discussion on any proposal to recharge the battery from the trolley wire when the battery-trolley locomotive is working.

One of the Special Regulations referred to limits the maximum voltage to 250 volts d.c., and in the case of Sandhole Colliery the installation appears to have given little trouble. Although there have been fatal and non-fatal electric-shock accidents at this voltage in some countries, the use of a pantograph might have prevented some of the accidents. A number of the Special Regulations were modified for Sandhole colliery following discussions, but although there are many 250-volt d.c. installations in United States mines, Mr. Wilkinson claims that this voltage may render a trolley scheme uneconomic.

There is no technical difficulty in increasing the maximum voltage to 500 volts or higher; the main point concerns the increased electric-shock risk associated with the higher and lethal voltage.

Another factor, chiefly economic, is the necessity for raising the height of the trolley wire for the higher voltages with consequently higher roadway.

In comparison with the German Regulations, with a minimum trolley-wire height of 1·80 m (6 ft) for voltages up to 220 volts d.c. and 2·20 m (7 ft 4 in) for voltages 220–550 volts, our Regulations call for a minimum height of 6 ft 6 in, with a reduction of 6 in in emergency.

Discussions between the Ministry and the N.C.B. may result in the solution of a number of problems which appear to be causing concern to the N.C.B.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. T. E. Green (*in reply*): Aspects of the braking problem have been raised by Mr. Crook, Mr. King and Mr. Butler. Power brakes on mine cars are undesirable, principally because the cost of the cars and the decking times will be increased. The application to a small number of cars in an ironstone mine is a problem of a different order from that facing the National Coal Board, with thousands in operation. Power braking on the train may eventually have to be adopted, but much development work, e.g. as instanced by Mr. King, must first be done. At present there are no mine cars in British coal mines fitted with either air or vacuum brakes.

Mr. Crook attributes to me (erroneously) the general statement 'special regulations act as a powerful deterrent', whereas my assertion was specifically in relation to the introduction of trolley or other types of locomotive. Mr. Crook's point is nevertheless fully appreciated, and one answer to his query is contained in Mr. Wilkinson's contribution, namely that the restriction of the voltage to 250 volts often makes it difficult to design an economic scheme.

Examination of the operation of compressed-air locomotives on the Continent has failed to convince me that they have any place in the haulage systems of British mines. The development of the electro-gyro locomotive has not progressed far enough to make any assessment of its possibilities in mining.

In answer to Mr. Crook's last two questions, I much prefer to see this problem met by maintaining a high standard of track and by the elimination of small-radius curves.

In reply to Mr. Newsam's query, coal in the past has been taken first from that part of the seam nearest the surface; continuing extraction 'in the seam' means that the roads go downhill, therefore the coal must be hauled out uphill. Horizon mining, as explained in Section 2.1, is based on a different principle.

Replying to Mr. Smith, the overall gear ratio of the motor and gear unit shown in Fig. 9 is 13·4 : 1. Only in a few instances has a right-angle drive been adopted by the manufacturers. The modern separators, e.g. of the micro-porous type to which Mr. Smith refers, have not been in use long enough to influence battery life.

At the present stage the resistance figures used for mine cars on good track (in the absence of any specific information) are: starting, 20lb/ton; running, 10lb/ton; braking, 5lb/ton. The statement in Section 8.2.2 to which Mr. Smith appears to be referring is based on this. In round figures, the initial cost of a 90h.p. 13-ton battery locomotive and a 100h.p. 15-ton Diesel locomotive are about the same. Certain difficulties have been experienced with the use of shuttle cars, and only a small number are still in operation.

I am grateful to Mr. Beasley for the additional information he has provided. In reply to Mr. King's last question, alkaline batteries may not, as yet, be used on underground locomotives.

The extra cost of the second cab is fully appreciated, but—in answer to Mr. Laycock—it is being provided, not because the driver cannot see far enough, but because in many cases he cannot see at all.* Persons permitted to occupy the second seat are defined in Paragraph 25 of the General Locomotive Regulations, and the difficulties mentioned by Mr. Laycock should not arise. The introduction of any new type of locomotive below ground is subject to the establishment of special regulations; the development of the electro-gyro unit is still at an early stage. The principal reason for the higher rate of installation of Diesel locomotives is that their manufacturers took great pains to design, build, sell and service their products for the period in question, whilst the battery-locomotive builders showed little interest.

Discussions between the Ministry and the National Coal Board are a continuing process, and the points Mr. Cowan mentions will doubtless be reviewed on appropriate occasions. It should be appreciated, however, that the successful installation at Sandhole Colliery, using 250 volts, is successful in a technical and operating sense only. The Board did not expect it to show any material economic advantage and have never claimed that it has done so. If we could have used 500 instead of 250 volts this aspect would have been transformed.

* For results of some investigations into this problem see GREEN, T. E.: 'A Progress Report on Underground Locomotive Haulage', *Transactions of The Institution of Mining Engineers*, 1952, 111, p. 828.

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Paper No. 2024 S
Apr. 1956

PHYSICAL PROPERTIES AND IMPULSE STRENGTH OF PAPER

By H. C. HALL, M.Sc., and E. KELK, M.Sc., A.Inst.P., Associate Member.

(*The paper was first received* 19*th October, and in revised form* 13*th December*, 1955. *It was published in April*, 1956, *and was read before a Joint Meeting of the* SUPPLY SECTION *and the* MEASUREMENT AND CONTROL SECTION 25*th April*, 1956.)

SUMMARY

It is shown that the impulse strength of oil-impregnated paper, measured on single sheets, is related to the impulse strength of a lapped dielectric using the same paper.

Attempts are made to relate the impulse strength to physical characteristics of the paper. General relationships involving apparent density and air impermeability are indicated, but it is shown that, in addition, account needs to be taken of some measurement of uniformity. Means for obtaining such a measurement on small areas of paper are described.

(1) INTRODUCTION

The effect of the physical characteristics of paper upon the electrical properties of impregnated paper dielectric has been much studied. There has been no general agreement on the most desirable characteristics of an insulating paper, the use of so-called 'high-density' paper, for example, being controversial. The subject is confused by the use of methods of assessing the physical characteristics of paper which do not fully take into account all major sources of variation affecting the electrical properties. This situation has no doubt arisen because of the tendency by the insulation engineer to use measurements of characteristics standardized by papermakers, ignoring the fact that these might have little or no relevance to his own applications.

The effect of paper characteristics upon electrical properties has been discussed by other workers.[1,2,3,4,5] Reference 6 deals with the impulse strength of lapped paper dielectric, and attempts to segregate effects arising from the nature of the paper. One conclusion of this work was that the properties of interest were being masked by properties of the paper which affected the electric strength, but were not revealed by standard tests.

Dealing with impulse strength alone, exploratory work indicated the importance of the paper structure. It was realized that hitherto standard methods of assessing uniformity were largely non-informative, as electrical failure was essentially a 'weakest link' phenomenon, and occurred initially over a minute area—an area much smaller than has so far been considered in framing specifications for paper tests.

The work to be described shows correlations between the electric strength of single sheets of paper and their physical properties. Some anomalies are, however, encountered, but it is shown that these can be explained by variations in the fine structure of the paper.

(2) ELECTRICAL AND PHYSICAL TESTS

A brief description is first given of the methods used for the measurement of the electric strength of impregnated paper, and of the physical properties of the unimpregnated paper with which correlation was sought. The electric strength is measured by an impulse test, as this is the criterion which is currently regarded as being the most important, and as such is called for, in specifications for high-voltage paper-insulated cables.

Mr. Hall and Mr. Kelk are with British Insulated Callender's Cables, Ltd.

(2.1) Impulse Breakdown Tests

The value obtained for the electric strength of impregnated paper depends upon the form in which it is tested. Values can be obtained, and have been reported, for paper lapped on to high-voltage cables, in the form of capacitors,[4] and in the form of cable models.[6] These methods were judged unsuitable for the present study, and a new testing technique was therefore developed for carrying out tests on single sheets of impregnated paper under uniform field conditions.

Examination of typical insulating papers showed that a reasonable measure of the variations in properties could be expected if the test area were defined by a circle of $\frac{1}{8}$ in diameter. The use of very large areas might have obscured the effect of important properties, while tests on very much smaller areas would have involved great technical difficulties.

(2.1.1) Description of Apparatus.

Essentially the impulse test cell consists of an ebonite container fitted with a lower silver-steel electrode. It is constructed to hold a quantity of the compound used for impregnating the sample under test, and has a machined ebonite top cover which houses the bearing for the top electrode contact. In a recess in the base of the container is placed a Paxolin paper-locating disc; this enables the electrodes to be arranged centrally with respect to the 1 in-square paper sample.

The electrode system adopted after considerable experiment is shown in Fig. 1. The upper electrode consists of a $\frac{9}{16}$ in-

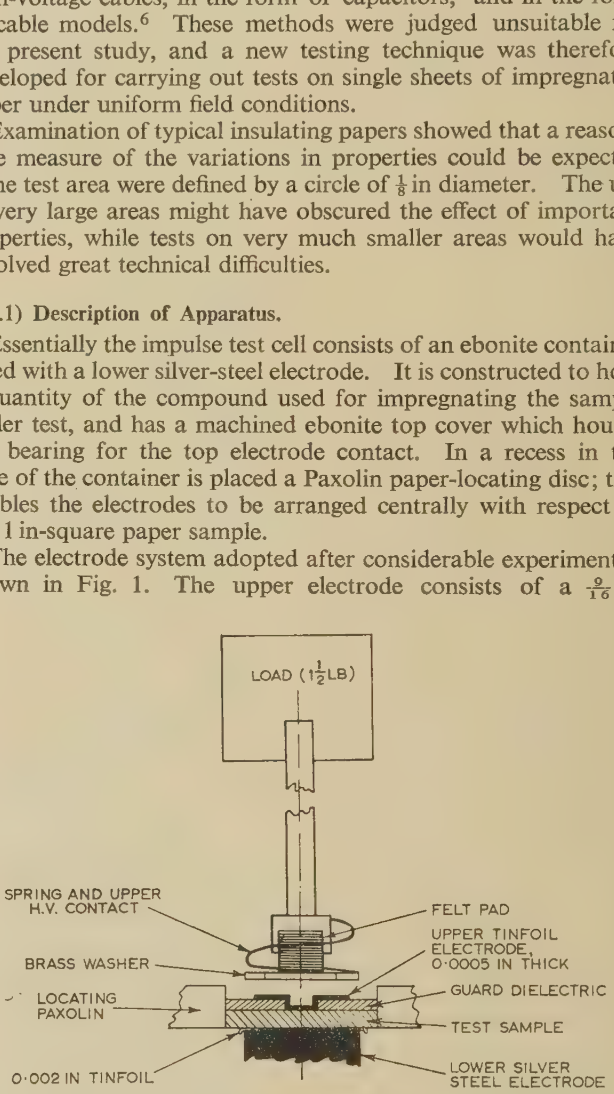

Fig. 1.—Schematic of electrode system.

diameter circle of tinfoil, 0·000 5 in thick, which is pressed into a $\frac{1}{8}$ in-diameter hole in the centre of a 1 in square of impregnated paper shown on the Figure as a guard dielectric. The impregnated test sample is held between this guard dielectric and 0·002 in-thick tinfoil covering (to avoid pitting) the lower silver-steel electrode, which is of $\frac{3}{4}$ in diameter. The part of the test sample under investigation is therefore automatically aligned

between the electrodes. Pressure is applied to the upper tinfoil electrode by means of a loaded felt pad, contact being effected through a brass washer which is in spring contact with the tinfoil.

The complete electrode system is immersed in the impregnating fluid used for the papers under test.

(2.1.2) **Impulse-Strength Results.**

A typical histogram of impulse breakdown voltage is given in Fig. 2 to show the variation which is found in testing single sheets of insulating paper by the above method.

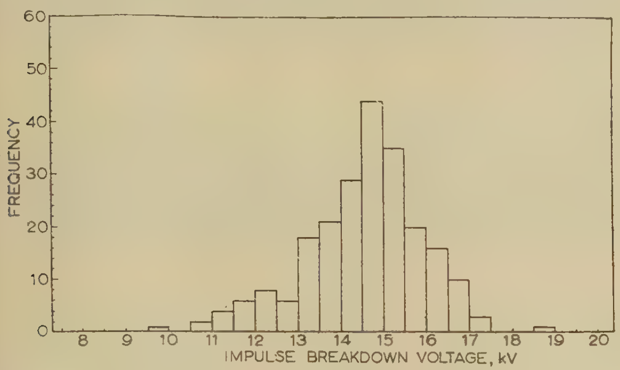

Fig. 2.—Typical impulse-breakdown-voltage histogram.
Mean: 14·5 kV.
Standard deviation: 14 kV.

It is important to show that the impulse strength measured in this way is related to the impulse strength of multi-layer lapped dielectrics. To demonstrate this, for each of a number of different papers a test was made in single-sheet form, and in the form of a model having about six layers of 1 in paper tape lapped on to a smooth cylinder; this type of model, described elsewhere,[7] closely simulates the dielectric in a full-sized cable. The impulse strength is computed, in the single-sheet test, from the thickness of the unimpregnated paper obtained, using an engineer's micrometer (see Section 2.2.2); in the case of the model, it is computed from the maximum stress (at the inner cylindrical electrode), using the total dielectric thickness measured, by micrometer, on the impregnated model cable after testing.

These two measures of electric strength will not be expected to be the same, owing to the presence of butt gaps in the cable models. The presence of these butt gaps introduces, in the cable model, a variation associated with paper thickness[6] of about 30% over the range of thicknesses used. This is allowed for by correcting the cable-model strengths to correspond to a constant paper thickness (3½ mils), and these corrected values are plotted against the corresponding values for single sheets in Fig. 3. The correlation may reasonably be taken to indicate that the single-sheet test gives results which are satisfactorily related to practical dielectrics in cable form.

(2.2) Physical Tests

(2.2.1) **Standard Paper Tests.**

Methods of determining the most useful physical and chemical properties of paper have been standardized for some time, each interested country having issued its own specifications. The British Paper and Board Makers' Association has been responsible for defining the testing methods in Great Britain. These all cover paper in bulk form—the form in which the papermaker is most interested. For example, in the standard method for the determination of the thickness of paper, a micrometer, having ¼ in² anvils and between which the force is 7·5 lb, is recommended;

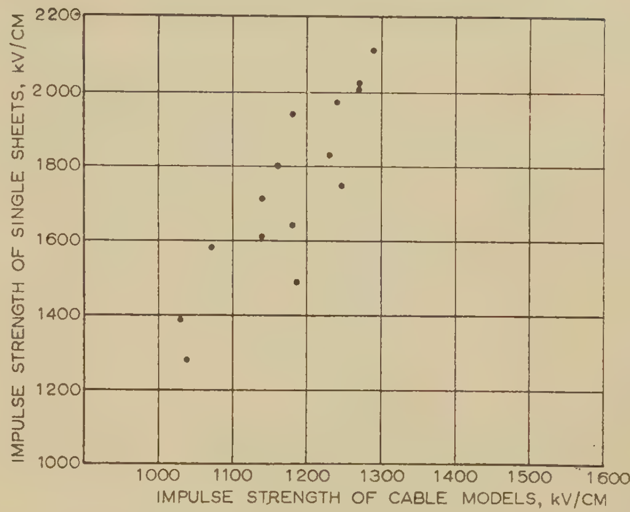

Fig. 3.—Relationship between tests on single sheets and cable models.

and again, the normal Gurley densometer air-resistance test measures air permeability of an area of 1 in².

(2.2.2) **Modified Physical Test Methods.**

For greater convenience in carrying out the initial experimental work discussed in the paper, modified methods of measuring physical characteristics were used:

(*a*) *Thickness.*—By the use of a standard engineer's micrometer reading to 0·000 1 in. (Mean of 50 determinations.)
(*b*) *Air impermeability.*—Time in seconds, for the flow of 0·25 cm³, using an orifice ½ in in diameter, with a pressure difference of 4·9 in of water, as in the standard Gurley densometer. (Mean of 50 determinations.)
(*c*) *Apparent density.*—Calculated from 'substance', in grammes per square metre, by weighing a sheet 100 cm² in area, and using the thickness obtained in (*a*). (Mean of 10 determinations of 'substance'.)

All physical tests were made under standardized conditions of humidity and temperature.

(2.3) Correlation of Electrical and Physical Characteristics

It is generally accepted that the electric strength of a given paper depends upon its density and its impermeability; and in fact, apart from subjective and non-quantitative assessments such as 'look-through', no other properties of the paper appear, in this connection, to have been considered.

Hence, initially, a number of papers differing widely in these characteristics was examined, covering a range of thicknesses from 1·5 to 7·5 mil. These papers were manufactured from sulphate wood pulp with the exception of one which was of 60/40 manila wood.

For these papers the impulse breakdown voltage is plotted against paper thickness in Fig. 4. There is a marked linear correlation (which is statistically significant) between breakdown voltage and paper thickness, the regression line being drawn through the origin. This linearity justifies the conclusion that electric strength, measured in this way, is independent of paper thickness, and hence can be used in examining the effect of the physical characteristics of the various papers. Variations in these physical characteristics account for the variations of breakdown voltage about the regression line.

The relationships between electric strength and air impermeability, and between electric strength and density, are shown in Figs. 5 and 6, respectively. Air impermeability, reduced to

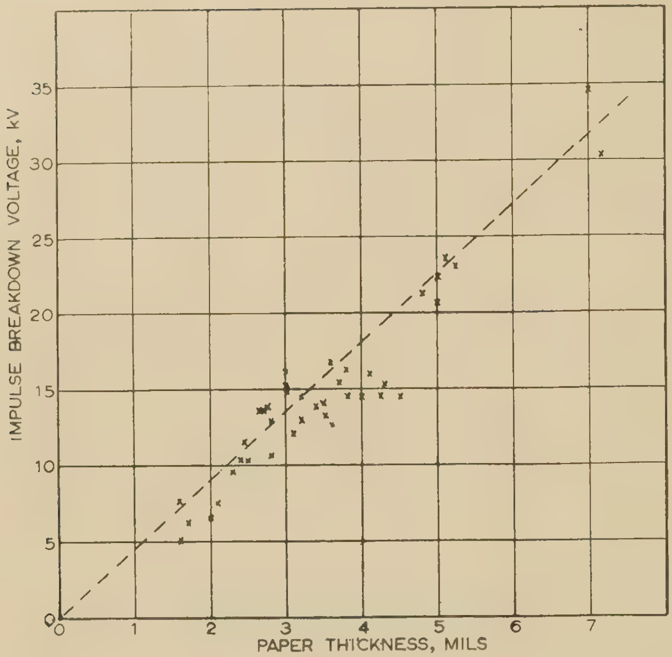

Fig. 4.—Impulse-breakdown-voltage/thickness results for a range of papers.

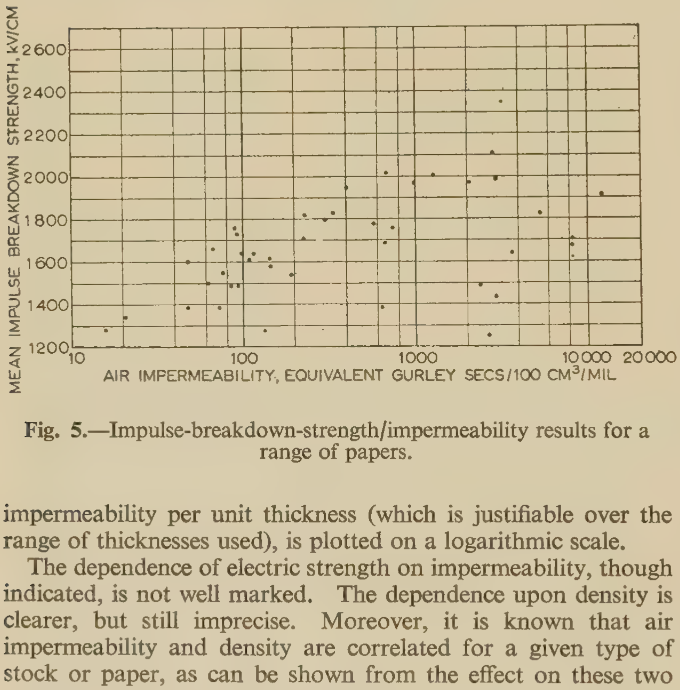

Fig. 5.—Impulse-breakdown-strength/impermeability results for a range of papers.

impermeability per unit thickness (which is justifiable over the range of thicknesses used), is plotted on a logarithmic scale.

The dependence of electric strength on impermeability, though indicated, is not well marked. The dependence upon density is clearer, but still imprecise. Moreover, it is known that air impermeability and density are correlated for a given type of stock or paper, as can be shown from the effect on these two variables of calendering the paper.

A statistical analysis was applied to the data in order to obtain estimates of the quantitative importance of apparent density and impermeability. Multiple regression analysis showed that the total variation in impulse strength (as measured by variance, i.e. square of standard deviation) could be allocated as follows:

Variation ascribable to thickness alone	2%
Variation ascribable to apparent density alone ..	60%
Variation ascribable to impermeability alone	19%
Variation ascribable to apparent density plus thickness plus impermeability	68%
Residual (unascribed)	32%

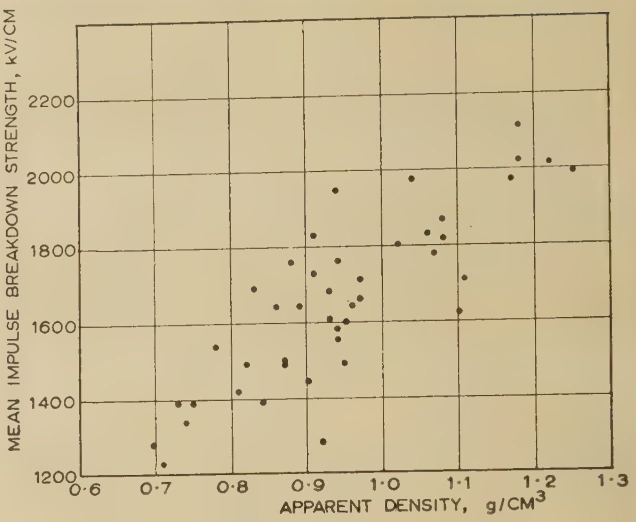

Fig. 6.—Impulse-strength/apparent-density results for a range of papers.

The relatively small advantage obtained by considering the simultaneous effects of density and impermeability arises from the fact that these two properties are, to some extent, correlated.

The high proportion, 32%, of the variation left unascribed strongly suggests the presence of other factors affecting the electric strength of oil-impregnated paper.

Preliminary work carried out to identify other factors indicated that good electrical characteristics appeared to be associated with a better formation, or uniformity of texture, as judged visually on the unimpregnated paper. This assessment is quite subjective and arbitrary, and methods were therefore devised to measure uniformity less arbitrarily, and quantitatively if possible.

(3) TESTS DEVELOPED FOR THE STUDY OF SMALL AREAS

(3.1) Site of Electrical Breakdown

A natural starting-point in the study of paper structure and its effect upon electric strength is the examination of the site of failure of a sheet of paper. Though the puncture, using the equipment described in Section 2.1.1, roughly takes the form of a circle less than 0·005 in in diameter surrounded by a carbonized ring, post-mortem examination reveals nothing of the local structure prior to breakdown as the whole of the area is destroyed. It therefore became apparent that the only way to determine the structure or 'look-through' of a paper prior to oil impregnation and impulse breakdown was to take a photograph of the area to be tested, for comparison with the same area of paper after breakdown. The procedure adopted is as follows:

The complete 1 in square of paper is placed on a photographic plate, and a contact negative is obtained using uniform illumination. After the paper has been impregnated and subjected to impulse breakdown test, it is degreased and placed in contact with the photographic negative, registration being facilitated by the use of dowel-pin holes in the paper. An examination of the area of breakdown is then made using a stereoscopic microscope with transmitted light, the negative being uppermost and the paper sample below.

Another method tried, which is, however, not so satisfactory as the first, is to use a projection microscope with a magnification of about 10 times, in order to obtain a photograph of the paper samples, not only before but also after electrical breakdown so that the two records can be examined side by side.

This experiment shows that, in all cases, electrical puncture

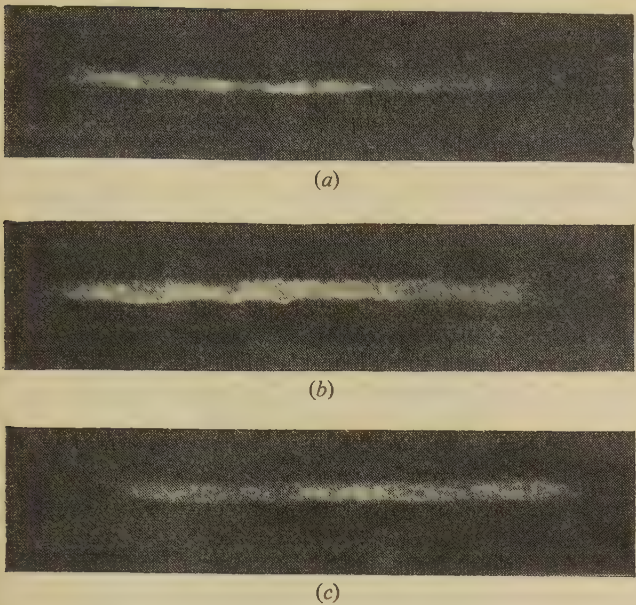

Fig. 7.—Typical cross-sections of insulating papers A, B and C.
(a) Paper A. (b) Paper B. (c) Paper C.

occurs at one of the more transparent spots of the paper under test.

(3.2) Sectioning Method

Another technique developed for the purpose of exploring the point of weakness of insulating papers is the microscopical examination of cross-sections of the paper, usually cut either along or across the machine direction. To obtain such sections, the use of sharp scissors was found to be quite satisfactory. Success with the microscopical examination depends upon the correct type of illumination, which must be vertically downwards upon the specimen whose upper surface only is brought into focus in the microscope.

Fig. 7 shows the type of section obtained by these means for three grades of insulating paper, identified as A, B and C.

It must be concluded that, even allowing for possible distortion of the paper surface by the cutting process, there still are very strong indications that normal grades of insulating paper are very non-uniform in thickness and flatness. This has been pointed out independently[8] for capacitor paper.

(3.3) Micro-Thickness Tests

For the purpose of investigating the thickness variations of a paper on a small scale, an electro-micrometer was modified to take ball anvils in order to make contact with the paper over a very small area. The force between the anvils is adjusted to be as small as possible (0·2 oz) to prevent distortion of the paper; a fiducial indicator ensures constant measuring pressure. In the type of instrument used, the mechanical movement of the fiducial indicator anvil controls the balance of an electrical network which includes a centre-zero milliammeter as a null indicator.

The two sizes of anvil mostly used are of $\frac{1}{8}$ in or $\frac{1}{16}$ in diameter.

In Fig. 8 is shown a histogram of thickness for a standard sulphate-wood cable paper (paper B) obtained by the use of a papermaker's standard thickness gauge. On the same diagram are also shown histograms obtained for the same paper by the use of the electro-micrometer, in one case with $\frac{1}{8}$ in-diameter ball anvils, and in the other with $\frac{1}{16}$ in-diameter anvils.

The decrease in the estimate of mean thickness, and the increase

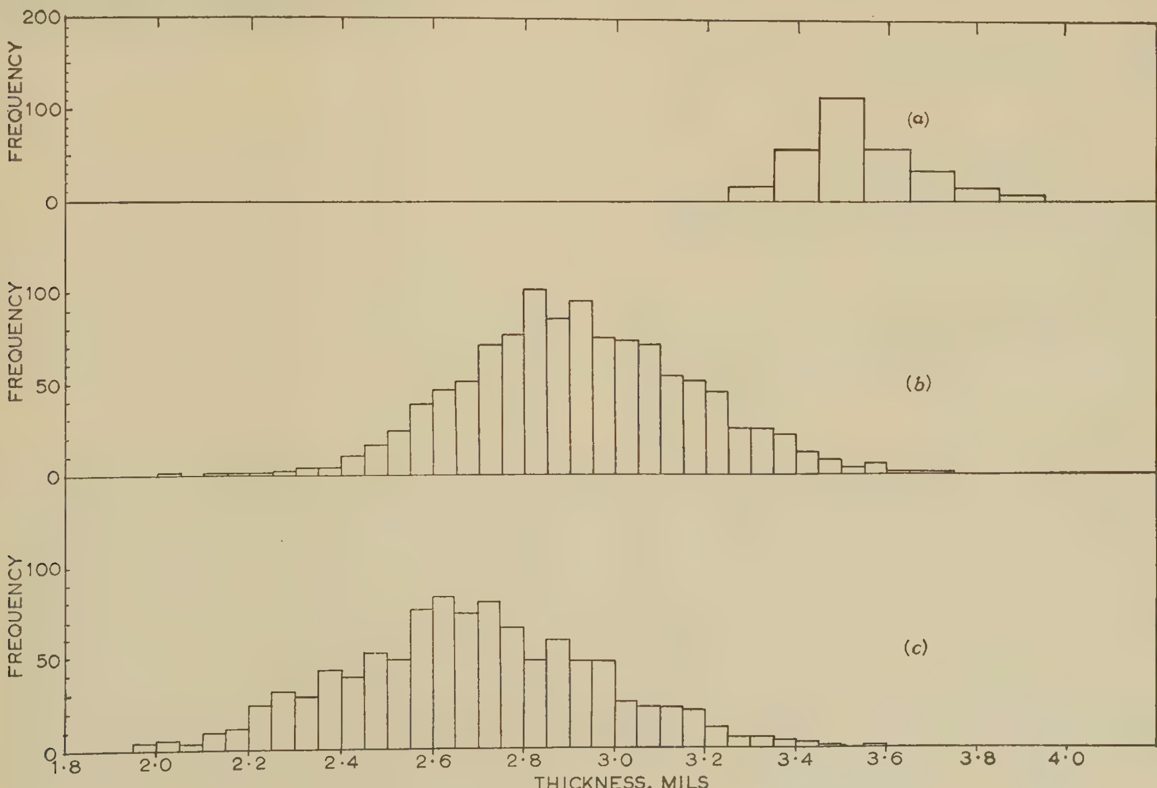

Fig. 8.—Thickness histograms—effect of anvil size. Paper B.

(a) Mean: 3·530 mils. Standard deviation: 0·133 mil. Measured by papermakers' thickness gauge.
(b) Mean: 2·916 mils. Standard deviation: 0·247 mil. Measured by electromicrometer $\frac{1}{8}$ in-diameter ball anvils.
(c) Mean: 2·680 mils. Standard deviation: 0·259 mil. Measured by electromicrometer $\frac{1}{16}$ in-diameter ball anvils.

in the standard deviation (measuring variation of thickness) as the size of the exploring anvils is decreased, is obvious from these histograms.

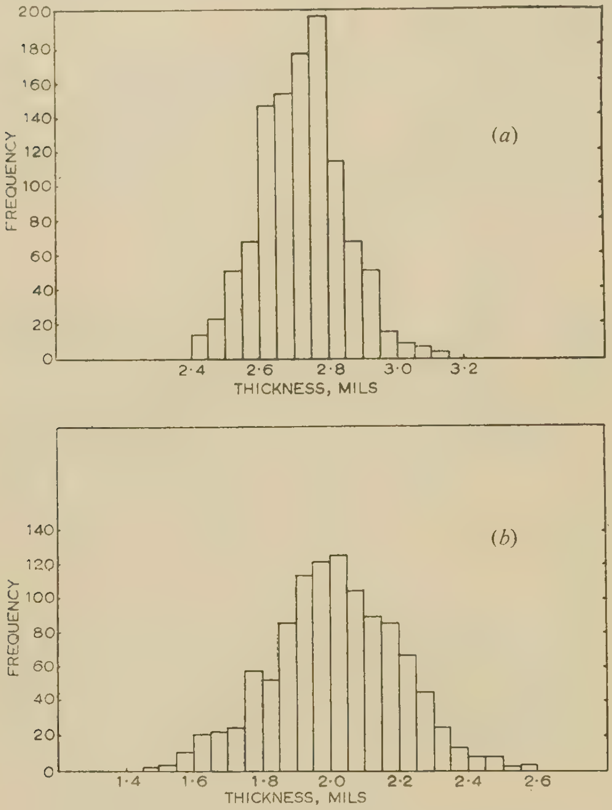

Fig. 9.—Thickness histograms for papers A and C.

(a) Paper C. Mean: 2·717 mils. Standard deviation: 0·12 mil.
(b) Paper A. Mean: 2·007 mils. Standard deviation: 0·19 mil.

Fig. 9 shows the difference between the thickness histograms for a well-beaten wood paper (paper A) of very non-uniform section, and a super-calendered high-density paper (paper C). These histograms, and those given in Fig. 8, were obtained on the same papers of which sections were shown in Fig. 7.

(3.4) Thickness-Scanning Experiments

It has been shown that electric breakdown occurs in the more transparent parts of the paper, and the observed thickness variations suggest that these transparent spots might correspond to thin areas. To establish this, small test areas were 'scanned' for thickness before electrical testing.

This procedure entails dividing up the area under test—in this case a circle of $\frac{1}{4}$in diameter—into small squares (at first of $\frac{1}{16}$in side) which can be scanned thoroughly using the electromicrometer described in Section 3.3. Later tests were made on a $\frac{1}{8}$in-diameter test area divided up into $\frac{1}{32}$in squares.

Each square within the grid is surveyed for its thinnest spot, so that a record is finally obtained of the minimum thickness in each small square of the test area.

After the thickness survey, the insulating paper is dried and impregnated in the usual way prior to impulse breakdown test. A transparent piece of graph paper, in which the lines correspond with the scanning grid, is then placed over the punctured paper sample so that the breakdown position can be located.

The result of 24 tests made with $3\frac{1}{2}$-mil sulphate-wood insulating paper showed that in 19 cases electrical breakdown had occurred in the grid square in which the minimum thickness for the complete test area had been recorded.

Thus it is concluded that points of local transparency are, in general, points of local thinness and of electrical weakness.

(3.5) Surface Uniformity Tests

The effect of reduction in anvil size, discussed in Section 3.3, makes it clear that limitations upon true thickness measurements are being imposed by the finite size of anvil. An alternative approach was therefore made, using a commercially available surface-uniformity gauge which permits the use, as exploring stylus, of a four-sided 90° diamond pyramid with a slightly rounded tip having a diameter of about 10^{-4}in. The load applied to the test specimen is of the order of 0·1 gramme.

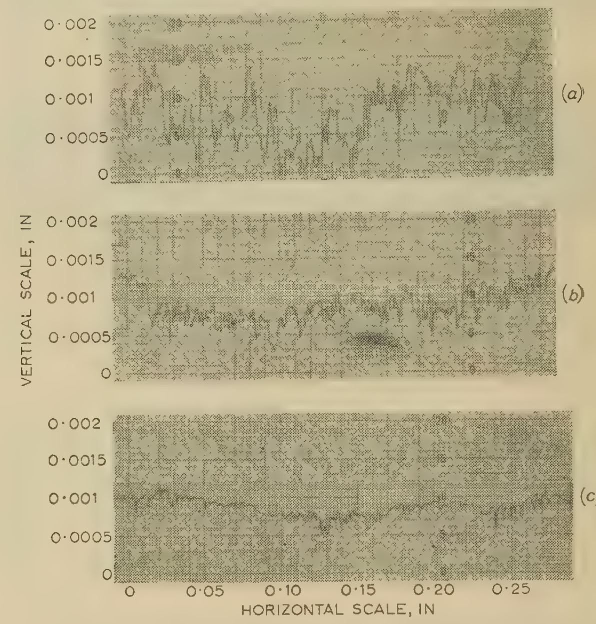

Fig. 10.—Typical surface profiles of papers A, B and C.

(a) Paper A. Mean c.l.a. = 150.
(b) Paper B. Mean c.l.a. = 105.
(c) Paper C. Mean c.l.a. = 55.

Fig. 10 shows surface-profile graphs, obtained with this instrument, of the three types of insulating paper (A, B and C) previously referred to. The correspondence in each case, in degree of uniformity indicated by the thickness histograms, the magnified cross-sections, and the surface-profile graphs, will be noted.

The surface-profile graphs include centre-line-average (c.l.a.) values as defined by B.S. 1134: 1950. These give a numerical assessment of surface uniformity.

This method of assessment applies to only one side of a paper, and does not provide accurate measurements of variations in total thickness. But it is nevertheless of value in indicating limits to, and with certain assumptions may indeed provide good estimates of, thickness variations.

(3.6) Air-Impermeability Tests

The association of electrical weakness with very local variations in paper structure suggested that the standard method of measuring air impermeability covered too large an area for good correlation with electric strength to be expected. Hence a study was made of air impermeability of areas as small as was practicable. This involved the design and construction of a new piece of equipment consisting essentially of the following main parts:

(a) A constant-pressure device for supplying air at a known pressure to the surface of the paper under test. This pressure can be measured on a water manometer by rotation of a two-way tap.

(*b*) A jig for holding the area of paper being tested against a standard aperture of $\frac{1}{16}$ in, $\frac{1}{8}$ in, or $\frac{1}{2}$ in diameter, respectively.

These jigs are designed to allow impermeability tests to be made either at a number of positions on paper tapes, or upon a defined area such as that enclosed by a $\frac{1}{8}$ in-diameter circle at the centre of a 1 in square. For this latter application accurate registration is obtained by means of either stops or dowel pins. Neoprene rubber, which has been bored out to the required size of aperture with the paper jig in the normally closed state, has been found the most suitable material for placing in contact with one face of the paper under test.

(*c*) A device which allows the rate of flow of air through the paper to be measured. A soap film, generated by the rotation of a glass helix which dips into a special soap solution, is formed at the entrance of a calibrated flow tube, and its passage down this tube is timed. This allows the rate of diffusion of air through the sample, placed in its jig in the air line preceding the soap tube, to be calculated.

In order that readings may be obtained speedily, the measured volume of air has been fixed at $\frac{1}{4}$ cm^3, with an air-pressure difference of 4·9 in of water (as in the Gurley instrument).

The effect upon impermeability measurements of using different sizes of orifice is shown by the histograms of Fig. 11, for a paper of fairly low impermeability (paper B). Decrease in the size of the orifice is accompanied by a large increase in variability of measurement, as well as a shift in the mean value. Since the variability will also depend upon the paper characteristics (e.g. the uniformity of impermeability over the surface), it is clear that it may be misleading, at the very least, to consider only mean values.

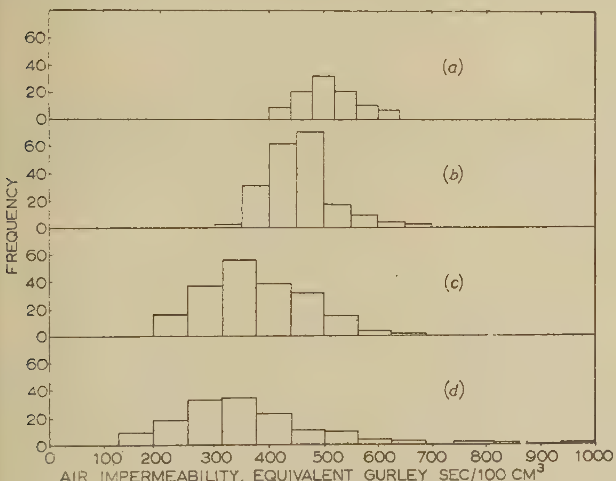

Fig. 11.—Histograms of impermeability—effect of orifice size.

(*a*) Gurley aperture. 1 in^2.
(*b*) $\frac{1}{2}$ in-diameter orifice.
(*c*) $\frac{1}{8}$ in-diameter orifice.
(*d*) $\frac{1}{16}$ in-diameter orifice.

(3.7) Transparency Tests

The papermaker uses the term 'look-through' to describe, in arbitrary terms, that visual characteristic of a paper which typifies uniformity of structure. This is clearly a very subjective assessment, especially for thicker papers, and recently look-through recording devices using a source of light and a photoelectric cell have been introduced into paper mills, the area under examination being usually of the order of 1 in^2. In view of the importance in an insulating paper of local transparency, as discussed in Section 3.1, equipment was constructed to measure the 'look-through', in terms of percentage light transmission, of small areas of paper.

For the same three papers A, B and C, for which thickness histograms are shown in Figs. 8 and 9, histograms of transparency were obtained with an aperture of $\frac{3}{64}$ in diameter. The histograms exhibited the same differences between three qualities of paper, in respect of range of transparency, as was previously shown by range of thickness variation. Since this size of aperture is considerably greater than the area in which electrical failure occurs, it is a reasonable surmise that the use of smaller apertures would emphasize such differences in quality as are important electrically.

In using much smaller apertures (of the order 0·01 in and less) it was considered more practicable and informative to obtain continuous records of transparency over a length of paper—similar to the records of surface profile discussed previously. In equipment devised for this purpose, the paper is passed between an illuminated orifice and a photo-multiplier tube. The output from this, after amplification, passes to a recording milliammeter, the rotation of the recording drum and the traverse of the paper under test being coupled mechanically. A record obtained in this way is shown in Fig. 12 for paper A used in previous illustrations, the aperture having a diameter of 0·006 in. Similar records, but with considerably larger apertures, have been obtained by other workers.[9]

(4) DISCUSSION

Clearly, a direct measurement of electric strength, such as the one described, probably gives the user of insulating paper all the information required for the assessment of electrical quality. But this method of assessment does not provide the information needed by the paper manufacturer to improve his product; instead, he needs information about those physical properties which affect the electric performance.

The foregoing results have been selected to illustrate, in various ways, methods of assessing the physical properties in a quantita-

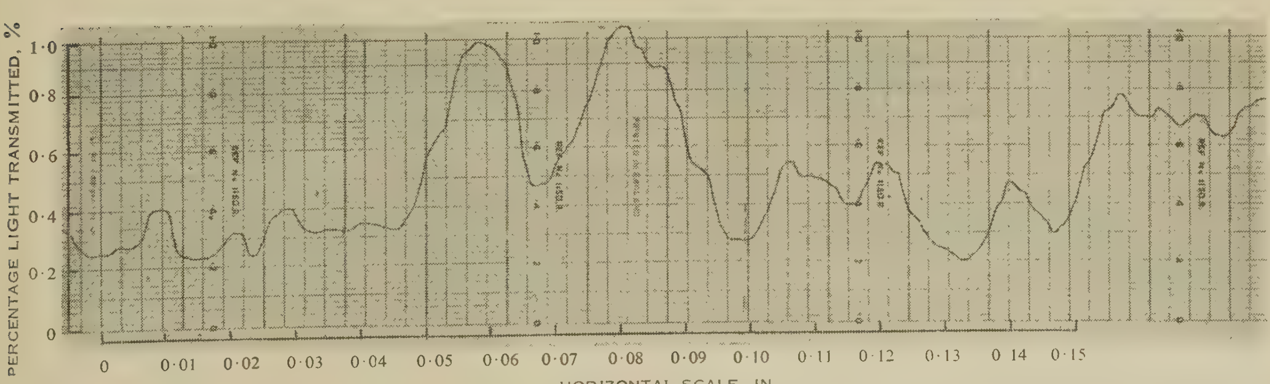

Fig. 12.—Transparency record for paper A using 0·006 in-diameter aperture.

tive manner, these methods being such as to measure the variation in these properties. Some of these illustrations show such differences in the variability, between different types of paper, of the characteristic being measured (e.g. thickness, transparency, surface profile) that it is rather surprising that any marked correlation at all is found between mean values, or values obtained on large areas.

It is apparent that the various measures of variability, or uniformity, depend very much upon the resolution of the measuring equipment, e.g. upon the size of anvil, aperture, etc. Best discrimination clearly would be obtained by the use of a stylus or orifice as small as possible, capable of following changes in paper characteristics over extremely small distances. Practical difficulties here impose obvious restrictions, and these are felt most in measuring the small-scale uniformity of just those two characteristics which have so far been accepted as the most important, namely impermeability and density.

The histograms shown in Fig. 11 show clearly the increase in variability, and hence the better measure of small-scale uniformity of impermeability, as the size of orifice is reduced. But with small orifices, measurement becomes not only extremely difficult, but also inherently very lengthy. With papers having high impermeabilities, one single measurement with an orifice $\frac{1}{16}$ in in diameter may take about half an hour, and since to obtain a representative frequency distribution at least 20 or 30 such measurements are needed, this approach is not desirable in routine application, though it may be valuable in special cases.

The variability of density, by weight measurements of very small areas, is not very satisfactory because of the low precision obtainable. A circle $\frac{1}{8}$ in in diameter of a 3-mil paper weighs only about $0 \cdot 000\,5$ gramme, and determination of weights to the nearest 10^{-5} gramme (representing a precision of only 2%) is just about achievable, but is too slow when, as before, at least 20 or 30 such determinations are required. This approach has, however, been explored, and it does provide useful information of a corroborative nature.

But bearing in mind that electrical failure takes place in an area much smaller than a circle $\frac{1}{8}$ in in diameter, it is clear that, though estimations of variability of impermeability (especially) and of density on the scales discussed provide useful indications of paper quality, they probably fall short of requirements when assessing a new paper. For much the same reason, measurement of variation of thickness, by the methods described, only goes part of the way to providing the information required. Measurements of surface profile or of transparency can, however, be made on a more appropriate scale. Though measurement of surface profile gives direct information about only one side of the paper, it is found that values of c.l.a., which measure surface uniformity quantitatively, are related to the electric strength.

This is demonstrated by extending the statistical analysis referred to in Section 2.3 to include c.l.a. divided by thickness as an additional variable. (Though division of c.l.a. by thickness is somewhat arbitrary, it is clear that some weighting of c.l.a. is necessary.) The result of this is to give the following allocation of sources of variation in electric strength, as percentages of the total variance:

Variation—total	100%
Variation ascribable to thickness	2%
Variation ascribable to apparent density	60%
Variation ascribable to thickness plus apparent density	61%
Variation ascribable to impermeability	19%
Variation ascribable to uniformity	28%
Variation ascribable to impermeability plus uniformity	$78 \cdot 5$%
Variation ascribable to apparent density plus impermeability	67%
Variation ascribable to thickness plus density plus impermeability plus uniformity	79%
Residual variation	21%

These results provide interesting confirmation of several conclusions which have already been indicated, namely:

Paper thickness has a negligible effect upon the strength of single papers.

That *single* property which accounts for most of the variability in strength is paper density. Impermeability or uniformity, alone, each account for much smaller proportions.

Impermeability and uniformity taken together account for a substantially greater part of the variation than density alone; in fact, practically all the ascribable variation can be accounted for by using these two parameters together.

Only 21% of the variation is left unascribed, and of this about 8% can be associated with experimental error. It is very probable that the remaining 13% would be reduced, were a less arbitrary measure of uniformity used.

The analysis shows, further, a marked negative correlation between apparent density and c.l.a./thickness, the correlation coefficient actually being $-0 \cdot 75$.

(5) CONCLUSIONS

Thus while, for the greatest impulse strength of a single sheet of paper, it is best, if one property only is to be specified, to choose a paper with as high an apparent density as possible, it is nevertheless considerably better to specify the paper in terms of a high impermeability and, at the same time, a high degree of uniformity.

While this has been demonstrated for uniformity of surface profile, it might be expected, in view of the photographic evidence that electrical failure is associated with the more transparent areas of the paper, that some measure of uniformity of transparency would be even more useful in specifying electrical quality.

(6) ACKNOWLEDGMENTS

Acknowledgments are due to Dr. L. G. Brazier, Director of Research and Education, British Insulated Callender's Cables Limited, for permission to publish the paper, and to the authors' colleagues for assistance with the measurements made.

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[The discussion on the above paper will be found on page 589.]

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Paper No. 2025 S
Apr. 1956

THE IMPULSE STRENGTH OF LAPPED IMPREGNATED PAPER DIELECTRIC

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SUMMARY

An investigation of the impulse strength of lapped impregnated paper dielectric has been made using model cables. The subjects studied include the effects of variation in the physical properties of the paper and the impregnant, the effects of variations in construction of the dielectric, and the effects of temperature and pressure. In addition, the response to different test procedures, such as polarity, polarity reversal and repeated stressing, has been examined.

The breakdown process, with impulse voltages, is discussed in the light of the results obtained. Both components—the paper and the oil—are shown to be effective in determining the impulse strength of the composite dielectric.

(1) INTRODUCTION

As a result of many years of intensive experiment, oil-impregnated paper dielectric has been developed to such an extent that it remains without a serious competitor in the field of high-voltage power cable insulation, though rubber-insulated cables have found limited applications at voltages up to about 35 kV. In service, cables are subject to high-voltage surges which arise on electrical power systems, so that, as well as giving satisfactory lengthy performance under sustained power-frequency voltages, the dielectric of a power cable is required to withstand over-voltages of a transient nature. For high-voltage cables, the impulse-withstand level is, at present, the most exacting specification requirement which has to be met, and in cable design the maximum operating stress is largely determined by the impulse strength of the dielectric.

An extensive laboratory investigation of factors affecting the impulse strength of lapped impregnated paper dielectric has been made, in view of the importance of this subject. Models have been used to study systematically the effects upon impulse strength of possible, or likely, variations in the physical properties of the two constituents, the oil and the paper, of the manner of assembly, and of variations in the method of measuring impulse strength.

Much of the published information on the impulse characteristics of cables deals with the effect of test conditions and test procedure, and the work has been carried out mainly with cables of the solid type. Davis[1] and Howard[2] have studied the influence of polarity, polarity reversal, repeated stressing, waveshape and conductor size. More recently, Priaroggia,[3] in addition to considering the effects of some of these variables, has dealt with the dependence of impulse strength upon temperature and applied gas pressure. The effects of certain variations in the constitution of impregnated paper dielectric, i.e. in the physical properties of the paper and the oil, have been reported by Domenach[4] and Hansson.[5] Salvage[6] has proposed an impulse breakdown mechanism for solid-type and gas-cushion cables based on the results of tests on both full-sized cables and cable models, and has attempted to relate the impulse strength of cables of these types to the electrical properties of the component dielectric materials.

The work reported in the present paper, involving tests on over 1 500 laboratory models, is concerned mainly with oil-filled cable dielectric, but dielectrics fully impregnated with compounds representative of those used in other types of cable have also been studied.

(2) EXPERIMENTAL METHODS

(2.1) The Test Specimens

The form of test sample used has already been described by one of the present authors,[7] but for convenience a short description is given.

The electrode system is a simple coaxial one, the inner electrode being a hollow tube, the outer being formed by a layer of metallic foil. For most samples the inner electrode has a length of 12 in and an external diameter of $\frac{5}{8}$ in. Paper tapes, usually 1 in wide, are applied helically over the whole length of this electrode in a simple winding jig which permits accurate control of tension, butt-gap width, angle of lay and registration. The outer electrode system consists of a tinfoil test electrode, 2 in long, and a coaxial guard electrode, also of tinfoil, 3 in long, wound centrally over the test electrode but insulated from it by paper applied in the same way as the main dielectric. Electrical connection is made to the test electrode by means of a narrow tinfoil tape passing through a small hole in the guard electrode.

This system can be used as a conventional 3-terminal one for measurement of power factor, etc., but for electric strength tests the two outer electrodes are connected together, when the function of the guard electrode is to alleviate stress concentration at the edge of the test electrode.

The thickness of dielectric most commonly used has been about 0·02 in, with a test-electrode to guard-electrode separation of about 0·006 in. This dielectric wall thickness permits the use of about six to eight layers of paper of the thickness commonly used in cables, and is considered to provide a dielectric which is representative of that in a full-size cable. A registration of 50/50 is, however, adopted, which is different from the 65/35 generally used in cables. (A registration of 65/35 implies that the edge of a tape divides the width of the underlying tape in the ratio 65 : 35.) This registration was chosen partly for ease of producing samples as similar as possible, but chiefly to ensure a distribution of electric stress (allowing for different permittivities of the paper and impregnant) which was, so far as possible, determinate and independent of number of papers or wall thickness.

Vacuum drying and impregnation are carried out in glassware under conditions which permit very close control of temperature. The process is described in greater detail in Reference 7.

In addition to the 12 in models, considerable work has also been carried out with 24 in inner electrodes. These are used to permit the use of greater thicknesses of insulation (up to about 0·1 in), and are convenient for studies of the effect of conductor diameter, stranding and screening, owing to the greater difference in electric stress which occurs at the inner and outer electrodes with increased dielectric thickness. The lapping and processing of these 24 in samples are similar to the methods used for the more usual 12 in samples, except that it is found necessary, because of the large wall thickness, to extend processing times and to use two concentric coaxial guard electrodes instead of

Mr. Hall and Mr. Skipper are with British Insulated Callender's Cables, Ltd.

one, as on the 12 in samples. This system then resembles an elementary form of 'condenser cone'.

For studying the effect of stranded conductors, a layer of copper or tinned-copper wires is applied helically to the inner electrode, to simulate the stranded conductor in an actual cable.

(2.2) Test Equipment and Procedure

A single-stage impulse generator of the conventional resistance-capacitance type, capable of producing standard 1/50 impulse waves up to a maximum output voltage of approximately 105 kV, has been used for the majority of the tests. The output capacitance is sufficiently large for the addition of the sample capacitance to have negligible effect on the output voltage and waveform.

In all the tests carried out, a nominal 1/50 microsec wave, conforming to B.S. 923: 1940, is used. The normal procedure adopted is to apply one impulse at each voltage level, commencing at a value of approximately 70% of the estimated breakdown voltage and increasing in steps of 3–4% until failure occurs. Failure is indicated by a small neon bulb connected across a capacitance in parallel with a resistance in the earth lead from the sample. Except where otherwise stated, the breakdown stresses quoted are those computed from the voltages at which failure occurred.

In making the breakdown tests at atmospheric temperature and pressure the miniature cables are placed in open baths containing compound similar to that used for impregnation. Tests at high temperatures are made by placing the test baths containing the samples in a large air oven fitted with a high-voltage bushing. In making tests at gas pressures above atmospheric a cylindrical pressure chamber consisting of a thick Paxolin barrel with brass end plates is used, capable of withstanding pressures up to 350 lb/in^2.

The dielectric wall thicknesses are measured by micrometer to enable the breakdown stresses to be computed. The breakdown paths through the dielectric are traced and the positions of the punctures with respect to the outer electrode noted.

(2.3) Design and Analysis of Experiments

Even with close attention to the control of processing and measurement, there is found to be, not unexpectedly, considerable scatter in test results, ascribable to variations in materials and minor variations in processing and measurement. For this reason, most of the work discussed in the paper has been conducted in a series of statistically designed experiments, with replication of samples sufficient to ensure that effects of a given order of magnitude (usually about 7%) would almost certainly be detected; the only exception to this procedure is the work discussed in Section 3.1.

To obtain a given amount of information, a smaller total number of samples is required if several variables are considered together in one major statistically designed experiment. In addition, measures are obtained of interactions between the factors involved. To enlarge the experiment beyond a certain point, however, is liable to introduce additional difficulties and sources of error, so that any actual experiment is in the nature of a compromise. With model cables, the most successful experiments have been found to be those involving two or three factors at two, three or four levels, the total number of samples being from 32 to 64. The designs used (usually so-called 'block experiments') are arranged in such a way as to eliminate, from the desired comparisons, effects due to variation in unwanted parameters not under control, e.g. day-to-day fluctuations in ambient conditions or batch-to-batch variation in quality of material.

The design and analysis of a typical experiment is set out in Appendix 8. Though statistical methods have been used throughout in analysing the results, it has been considered unnecessary to give the analyses in detail. In discussing each experiment, an indication of the result of the analysis is given by the use of the terms 'significant' or 'highly significant', referring to comparisons for which, respectively, a 5% or a 1% probability exists of the effect quoted having arisen by chance. An effect associated with a probability appreciably greater than 5% is referred to as 'non-significant', i.e. it can be ascribed to random experimental variations.

This procedure permits the presentation of mean values only in the Tables and Figures, and simplifies the appreciation and discussion of the physical considerations.

The basic parameter used in assessing statistical significance is the variance, σ^2, where σ is standard deviation. It must be recognized that only experimental estimates, s^2, of σ^2 are available, and that s^2 itself is subject to experimental variation. Individual values of s are therefore not quoted, but a careful scrutiny of the values obtained from experiment to experiment is made to check that there is no statistically significant variation of the experimental error.

In the text each major experiment is numbered, and may be referred to in different Sections, as the results obtained may be used in discussing the effect of several distinct variables.

(2.4) The Papers

Most cable insulating papers are manufactured from wood pulps, although some manila and manila-wood papers are used for certain applications, particularly where good tearing resistance is required. Most of the papers used in the investigations were sulphate-wood papers, one being a 60/40 manila-wood paper. With the exception of paper 5, which was of American manufacture, all were supplied by British mills.

Relevant physical characteristics of the eight papers used in all Sections, except Section 3.1, are given in Table 1, the papers being numbered to facilitate identification. In dealing with the effect of the physical properties of the paper in Section 3.1, a further 24 papers of different types were used.

Table 1

Paper number	Type of paper	Nominal thickness	Apparent density	Impermeability
		mils	g/cm^3	Gurley seconds/100 cm^3/mil
P.1	Wood	2·5	0·89	100
P.2	Wood	3·5	0·94	100
P.3	Wood	5·0	0·91	100
P.4	Wood	7·5	0·97	70
P.5	Wood	3·0	1·18	3 000
P.6	60/40 Manila Wood	4·0	0·74	35
P.7	Wood	2·5	0·86	3 600
P.8	Wood	3·5	0·82	90

(2.5) Impregnating Compounds

As in current British cable practice, all the oils used are naphthenic-base oils with a high proportion of aromatics. Oils C.1. and C.2 and the oil used in the compound C.5 are derived from low-sulphur low-wax crude oils of South American origin, subjected after distillation to 95% acid and clay treatment. Oil C.3 is refined from North American crude oils.

The oils and compounds used as impregnants in the investigation described in the paper are given in Table 2.

Table 2

Compound number	Description	Viscosity at 25° C
		centistokes
C.1	A light mineral oil used in oil-filled cables	25
C.2	A light mineral oil used in oil-filled cables	13
C.3	A refined mineral oil used in Oilostatic cables	2 300
C.4	A compound consisting of 73% by weight of C.3 and 27% by weight of low-molecular-weight polyisobutylene used in impregnated pressure cables	8 000
C.5	A refined mineral oil with approximately 15% by weight of refined resin, used in solid-type cables	10 000

(3) EXPERIMENTAL RESULTS

In presenting the results obtained it is convenient to segregate variations in the different components, oil and paper, in the manner of construction, in the testing procedure, and in electrode effects. This does not imply that these variations are independent in their effects—in fact, it is shown that several important interactions exist which are discussed where appropriate.

(3.1) Effect of Variations in Physical Properties of the Paper

The chief physical properties of insulating paper which are of interest to the cablemaker are thickness, apparent density and impermeability. In the manufacture of paper it is not possible to vary these properties independently, except over limited ranges; this makes it difficult to determine directly the separate effects of these properties on the impulse strength of lapped impregnated-paper dielectric. The method adopted, therefore, has been to consider the results obtained on a large number of papers covering a wide range of physical characteristics, and to use statistical treatment to measure the effect of each variable.

In all, 21 different papers were used with C.1 oil as impregnant, including those listed in Table 1, and 13 with C.4 oil as impregnant—a number of the papers being used with both impregnants. For each paper, in addition to impulse strength, measurements were made of thickness, density, air impermeability and surface uniformity, as follows:

Thickness.—Thickness was deduced from dielectric thickness on the model cable, after testing.

Density.—Density was deduced from the weight of 100 cm^2 of paper, and from 'normal' thickness measured by an engineer's micrometer.

Air impermeability.—Air impermeability was deduced from the time of flow of 0·25 cm^3 of air through a circle of paper $\frac{1}{2}$ in in diameter with a pressure difference of 4·9 in of water as in the standard Gurley densometer. This is converted to the time of flow of 100 cm^3 through an area of 1 in^2 (i.e. Gurley seconds), and divided by 'normal' thickness.

Uniformity.—Uniformity was assessed using a commercial instrument recording surface profile, and measuring centre line average (c.l.a.), as defined in B.S. 1134: 1950.

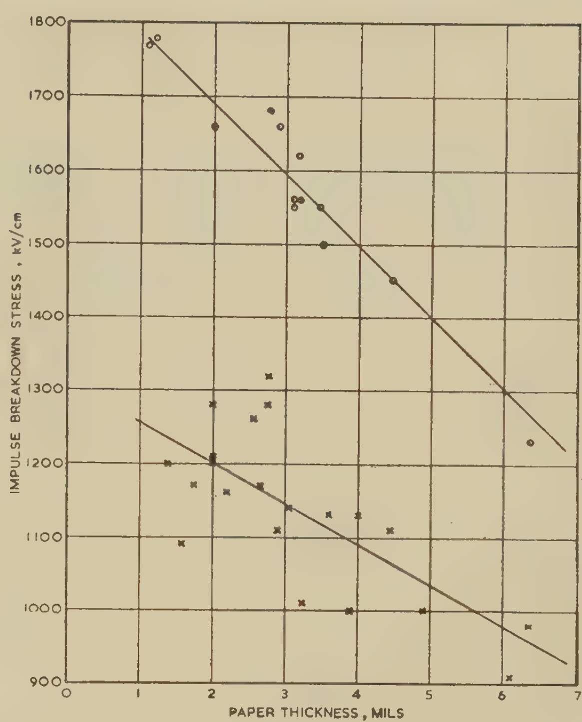

Fig. 1.—The effect of paper thickness on impulse strength.
Each point represents the mean of at least 10 individual results.
○ C.4 impregnated papers.
× C.1 impregnated papers.

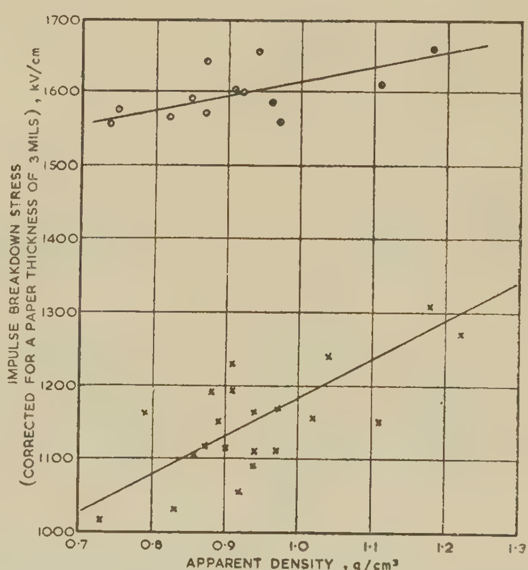

Fig. 2.—The effect of paper density on impulse strength.
Each point represents the mean of at least 10 individual results.
○ C.4 impregnated papers.
× C.1 impregnated papers.

General relationships between impulse strength, thickness and density are shown in Figs. 1 and 2. Fig. 1 suggests very marked and approximately linear decreases of impulse strength with increase of paper thickness, over the range considered, with both C.1 and C.4 oils as impregnants. In Fig. 2, which shows the effect of paper density, the effect of paper thickness has been eliminated by correcting all impulse strengths to correspond to a paper thickness of 3 mils. For both impregnants an increase of strength is suggested with increase of paper density, but the increase is much less marked with the more viscous impregnant.

There is clearly a large residual variation with the less viscous impregnant, but the residual variation in the case of C.4 oil is only of the same order as the experimental error, and thus does not warrant further consideration. More precise treatment, by

statistical methods, was therefore applied to the data for which C.1 oil was used, taking into account impermeability and uniformity, as these properties are more sensitive to local variations in paper structure, and might be expected to correlate more closely with electrical failure, which is a very localized phenomenon.

A multiple regression analysis was made to examine the dependence of impulse strength upon paper thickness, density, log (impermeability) and uniformity, measured as (c.l.a./thickness). It appeared that density and (c.l.a./thickness) were negatively correlated, and that impermeability and density were to a certain extent interrelated, for the particular papers examined.

The analysis shows that, of the total observed variation in impulse strength, approximately 52% can be ascribed to the effect of paper thickness. A further 24% can be associated with density. Alternatively, the additional variation can be ascribed (possibly preferably), instead of to density, to the combined effect of impermeability and uniformity, the actual contribution for this last combination being 26%. Thus nearly 80% of the total variation in impulse strength can be accounted for in either of these ways. The residual variation is not significantly reduced by considering the effect of all variables together, which accounts for 81% of the total variation. Thus only 19% of the total variation remains unascribed to measurable parameters, and of this, part must be regarded as experimental error. Analysis shows that this allowance amounts to at least 5%. It is safe to conclude, therefore, that nearly all, if not all, of the major factors associated with the physical properties of the paper, which affect the impulse strength of a lapped dielectric, are accounted for. Possibly further study of better methods of measuring uniformity might yield more conclusive evidence upon this point. The measure actually used here is to some extent arbitrary, weight being given to the fact that a given degree of non-uniformity is more serious in a thin paper than in a thick one, by dividing c.l.a. (itself somewhat arbitrary) merely by paper thickness.

Thus the analysis as a whole, applied to papers impregnated with C.1 oil, leads to the conclusions that

(*a*) The impulse strength of lapped dielectric decreases as the thickness of the paper tapes is increased, and this effect is more important than all other properties of the paper.
(*b*) Impulse strength increases with increase in paper density.
(*c*) Impulse strength increases with increase of impermeability and uniformity, and though the separate effects are smaller than that of density alone, the combined effect is at least as great and may be greater.

Statistical analysis shows that the variance of individual observations of impulse strength increases significantly as the uniformity of the paper decreases. For three typical papers on which a sufficient body of data is available to give reasonable estimates of variance, the following data are obtained:

Paper number	C.L.A. divided by thickness	Standard deviation
		kV/cm
P.5	20	69
P.2	30	78
P.7	70	135

A separate study of the effects of the physical properties of paper on the impulse strength of single sheets of impregnated paper, as distinct from the lapped multi-layer dielectrics considered in the paper, is described elsewhere.[8]

(3.2) Effects of Variations in Construction

In this Section the effects upon impulse strength of factors which it is possible to vary during the lapping operation are considered, such as registration, butt-gap dimensions and lapping tension. All samples were lapped under ambient laboratory conditions of temperature and humidity.

(3.2.1) Registration.

The reasons for the general use of a 50/50 registration in the lapping of the cable models have already been stated in Section 2.1. A 50/50 registration is not employed in full-sized cables, for which a 65/35 registration is most commonly used.

The registration determines the relative numbers of oil channels and paper tapes in the radial paths through the dielectric with which breakdown is associated. In studying the variation of impulse strength with registration, nominal registrations of 50/50, 65/35 and 75/25 were used to produce dielectrics in which one, two and three paper tapes, respectively, were in series with each oil channel. Twelve layers of paper tapes were employed so that, for each case, all radial paths through the dielectric included the same number of oil channels and paper tapes. The results are given in Fig. 3, from which it can be seen that the

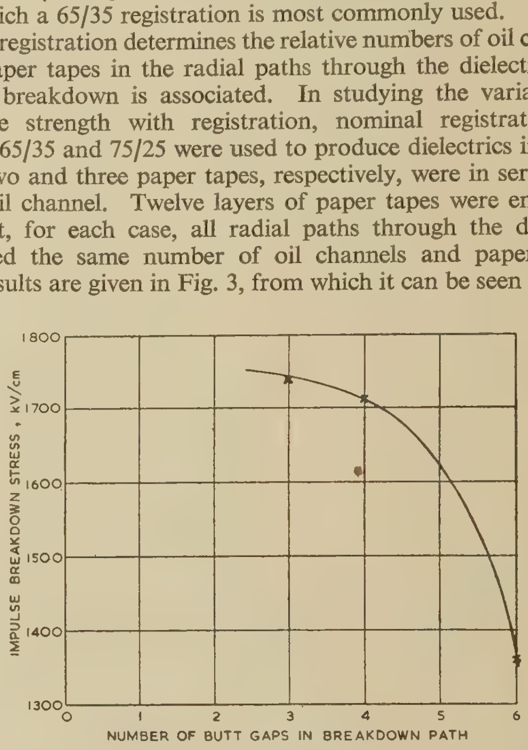

Fig. 3.—The effect of registration on impulse strength.

Experiment No. 1.
Paper: P.5.
Impregnant: C.1.
Number of replicates: 10.

impulse strength increases as the number of oil channels in the breakdown path is reduced. The departure from linearity of the regression line is statistically significant.

(3.2.2) Butt-Gap Depth.

This experiment was designed to determine the relative contributions of butt-gap depth and paper-tape thickness to the observed variation of impulse strength with paper thickness, discussed in Section 3.1. Normally the radial depth of the butt gap is equal to the paper thickness, except when a reversal of lay is introduced during the lapping operation. Miniature cables were therefore prepared with two and with three layers of nominal $2\frac{1}{2}$ mil paper superimposed, to produce dielectrics with butt gaps having depths of 5 mils and $7\frac{1}{2}$ mils, and these were compared with samples wound in the normal fashion with 5-mil and $7\frac{1}{2}$-mil papers. Samples lapped in the usual manner with $2\frac{1}{2}$-mil paper were also included in the experiment.

The results, which are plotted in Fig. 4, show that, for a given butt-gap depth, there is no significant effect due to paper thickness, but the decrease of impulse strength with increasing butt-gap depth is, however, highly significant. This implies that the variation of impulse strength with paper thickness is largely, if not entirely, due to the resulting changes in the radial depth of the butt gap.

Fig. 4.—The effect of butt-gap depth on impulse strength.

Experiment No. 2.
Impregnant: C.1.
Number of replicates: 12.
× 2·5-mil paper tapes (P.1).
○ 5·0-mil paper tapes (P.3).
△ 7·5-mil paper tapes (P.4).

(3.2.3) **Butt-Gap Width.**

The width of butt gap employed in lapped impregnated-paper dielectric is largely determined by the degree of mechanical flexibility required. The relationship between impulse strength and butt-gap width has been studied using cable models having conductor diameters of $\frac{5}{16}$ and $\frac{5}{8}$ in, and the results are given in Fig. 5. For both conductor diameters, closing up the butt-gap width to zero from the normal value of $\frac{1}{16}$ in increases the impulse strength by nearly 20%, whereas doubling the normal $\frac{1}{16}$ in gap has a very small effect.

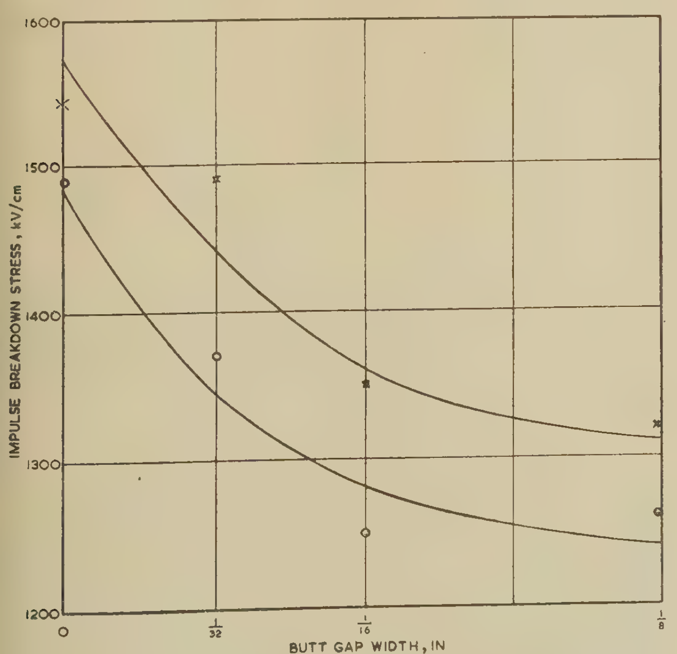

Fig 5.—The effect of butt-gap width on impulse strength.

Experiment No. 3.
Paper: P.5.
Impregnant: C.1.
Number of replicates: 12.
× 5/16 in-diameter conductors.
○ 5/8 in-diameter conductors.

(3.2.4) **Lapping Tension.**

For most of the work described a load of 5 lb weight has been applied to each paper tape during lapping. The use of a constant mechanical load gives rise to a variation of tensile stress in the paper with different paper-tape widths and thicknesses. In order to determine whether the dependence of impulse strength on paper thickness was partly or wholly ascribable to the variation of mechanical stress in the paper, the effect of paper tension over a wide range has been investigated with both a thin and a thick paper.

The results of these tests are given in Table 3, which shows that variation of the lapping load from 1 to 10 lb weight is without significant effect on impulse strength. It may therefore be assumed that the relationship between impulse strength and paper thickness is not due, to any significant extent, to variation in tensile stress in the paper during application.

Table 3

Effect of Lapping Tension on Impulse Strength

Experiment No. 4. Impregnant: C.4

Weight on each 1 in-wide tape	Paper	Nominal paper-tape thickness	Number of tests	Mean impulse breakdown stress
lb wt.		mils		kV/cm
1	P.1	2·5	8	1 680
10		2·5	5	1 640
1	P.4	7·5	7	1 230
10		7·5	6	1 280

(3.3) Influence of External Test Conditions

Variation of the ambient temperature and pressure conditions under which impulse breakdown tests are made mainly affects the oil phase of impregnated-paper dielectric. In considering the effect of temperature on impulse strength, it is therefore convenient to discuss also the influence of compound viscosity and type of compound, and similarly the effects of gas pressure and degree of impregnation of the dielectric are related.

(3.3.1) **Temperature and Compound Viscosity.**

Impulse tests over a range of temperatures have shown that the change in impulse strength with temperature is significantly related to the viscosity/temperature characteristic of the impregnating compound, a large change in impulse strength being associated with a large change in compound viscosity (see Table 4).

An exception is provided by the compound C.5, which is the only one studied containing colophony rosin. Fig. 6 and Table 4 show that, with straight oils and those containing purely hydrocarbon additives, the impulse strength of impregnated-paper dielectric is dependent upon the viscosity of the impregnant, the independent effects of test temperature and type of compound being relatively small. It may be remarked that changes in compound density with temperature and with type of compound are very small, and cannot account, to any appreciable extent, for the observed differences in impulse strength.

The results presented in Table 4 were obtained using a paper of medium density and impermeability. The data given in Table 5 show that the variation of impulse strength with temperature using an impregnant of high viscosity is significantly reduced in the case of a high-density high-impermeability paper.

Table 4

INFLUENCE OF COMPOUND VISCOSITY ON IMPULSE STRENGTH

Paper: P.8

Number of replicates: 8

Experiment No. 5

Impregnation compound	Viscosity at 20° C	Mean impulse breakdown stress at 20° C	Viscosity at 85° C	Mean impulse breakdown stress at 85° C	Ratio of viscosities at 20° and 85° C	Percentage reduction in impulse strength over the temperature range 20°–85° C
	centistokes	kV/cm	centistokes	kV/cm		%
C.5	20 000	1 390	82	1 120	244	21
C.4	13 500	1 550	115	1 130	117	32
C.3	3 500	1 470	35	1 080	100	31
C.1	32	1 160	4·8	1 120	6·7	3·7
C.2	15	1 120	2·7	1 090	5·5	2·7

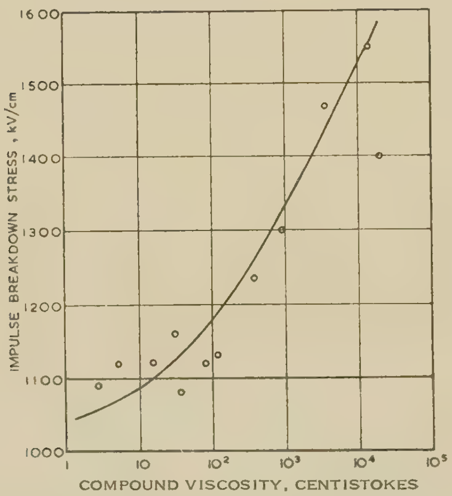

Fig. 6.—The effect of compound viscosity on impulse strength.

Experiment No. 5.

Table 5

EFFECT OF PAPER PROPERTIES ON THE IMPULSE-STRENGTH/TEMPERATURE RELATIONSHIPS

Experiment No. 6. *Impregnant: C.*4
Number of replicates: 8

Test temperature	Compound viscosity	Paper	Paper density	Paper impermeability	Mean impulse breakdown stress 5/16 in conductor dia.	Mean impulse breakdown stress 5/8 in conductor dia.
°C	centistokes		g/cm³	Gurley seconds/mil	kV/cm	kV/cm
20	13 500	P.2	0·94	100	1 840	1 660
		P.5	1·18	3 000	1 840	1 700
85	115	P.2	0·94	100	1 180	1 100
		P.5	1·18	3 000	1 370	1 270

(3.3.2) **Applied Gas Pressure and Degree of Impregnation.**

The results of tests at different gas pressures and degrees of impregnation are given in Table 6. This shows that the impulse strength of fully-impregnated paper dielectric is independent of applied nitrogen pressure up to 300 lb/in². On subjecting the dielectric to a draining process sufficiently severe to remove most of the compound from the butt spaces, the impulse strength varies to a highly significant extent with applied nitrogen pressure.

Table 6

EFFECT OF APPLIED NITROGEN PRESSURE ON IMPULSE STRENGTH

Experiment No. 7. *Paper: P.*6

*Impregnant: C.*4

Number of replicates for each mean: 4

Applied nitrogen pressure	Mean impulse breakdown stress: Fully-impregnated dielectric	Mean impulse breakdown stress: Drained dielectric
lb/in² above atmospheric	kV/cm	kV/cm
0	1 500	620
50	1 440	—
100	1 520	—
200	1 440	1 450
300	1 500	—

The impulse strength of fully impregnated dielectric is pressure-dependent when a large number of impulses is applied at or near the breakdown level (see Section 3.4.2).

(3.4) Effect of Variations in Test Procedure

It has been reported that the impulse strength of high-voltage power cables is dependent upon the polarity of the voltage applied to the conductor and is modified by repeated applications of stress. It is also common practice to test cables using ten positive followed by ten negative impulses at each voltage level, and conflicting results have been published on the effect of a reversal of polarity. The effects of such variations in test procedure have been examined.

(3.4.1) **Influence of Polarity.**

The results of the two experiments designed specifically to study the effect of conductor polarity on impulse strength are

Table 7

EFFECT OF CONDUCTOR POLARITY ON IMPULSE STRENGTH

Paper: P.2

Experiment No.		8	9	9
Conductor diameter, in		0·625	0·312	0·312
Conductor stress/sheath stress		1·06	1·15	1·15
Impregnating compound		C.1	C.1	C.4
Polarity of conductor: Positive	Number of tests	12	9	9
	Mean breakdown stress, kV/cm	1 140	1 270	1 600
Negative	Number of tests	12	9	9
	Mean breakdown stress, kV/cm	1 120	1 230	1 580

summarized in Table 7. Experiment No. 8 shows that, with a stress difference of 6% between conductor and sheath, there is no dependence of impulse strength upon polarity; the conductor diameter is reduced and the dielectric wall thickness is increased in experiment No. 9 so that this stress difference is increased to 15%. In addition, since with full-sized cables a polarity effect has been observed with solid-type but not with oil-filled cables, both high- and low-viscosity impregnants are used. Again, it is found that the polarity of the conductor has no significant effect upon the impulse strength.

There is a slight tendency in all three comparisons made for the strengths to be greater with the conductor positive, but the differences are too small to be judged significant.

(3.4.2) **Repeated Stressing.**

The effect of increasing the number of applications of stress at each voltage level is shown in Table 8. An increase from 1 to 20 applications causes no detectable reduction in impulse strength. The absence of an appreciable effect in this case is confirmed by the observation that, in nearly every case with repeated impulses, failure occurs at the beginning of the group of 20 impulses at the breakdown level. 200 impulses at each voltage level cause a significant reduction in breakdown stress, and with this measure of repeated stressing the impulse causing failure is more or less randomly distributed throughout the group of 200.

It is found that with 200 impulses at each level, as with single impulses, there is no polarity effect with the type of sample used. The breakdown strength with 200 impulses at each level is significantly increased by the application of 200 lb/in^2 nitrogen pressure.

The decrease of approximately 13% in the breakdown strength, as the number of applications at each voltage level is increased from 1 to 200, is statistically highly significant and is in good agreement with the results obtained by Howard and Davis on full-sized cables. Howard[2] found that the application of 100 impulses at each level caused a 10% reduction in impulse strength, and Davis[1] observed a similar reduction using groups of 200 impulses.

(3.4.3) **Polarity Reversal.**

In experiment No. 8 in Table 9 the four test conditions studied were single impulses of either polarity at each voltage level, 20 impulses of the same polarity, and 10 positive followed by 10 negative impulses. Since the application of 20 impulses at each level is found to cause no reduction in the breakdown strength compared with single impulses, it is concluded that any effect obtained by using 10 positive followed by 10 negative impulses at each level, rather than a single impulse, is due to the reversal of polarity, and not to repeated stressing. In subsequent experiments, therefore, the effect of polarity reversal is measured by a comparison of the two impulse strengths—10 positive followed by 10 negative impulses and a single impulse at each voltage level.

The data in Table 9 show that, with the low-viscosity oils C.1 and C.2 as impregnants, the reduction in impulse strength due to polarity reversal is approximately 12%, which is highly significant. The results in the final column indicate that the effect is not appreciably different when a high-impermeability high-density paper is used. With a high-viscosity impregnant, C.4 compound, the polarity-reversal effect is increased to about 20%, which is significantly greater than the effect with the low-viscosity oils.

There is a strong tendency for failure to occur on the first impulse applied after a reversal of polarity. In all the tests made with 10 positive followed by 10 negative impulses at each voltage level, nearly 80% of the failures occurred on the first impulse after reversal, another 10% on the second impulse and a further 5% on the third impulse. Since a polarity reversal from negative to positive is accompanied by an increase in voltage, small compared with the observed polarity reversal effect, it would be expected that there would be a slightly greater tendency for breakdown to occur on positive impulses, even in the absence of a polarity effect. This is in fact found to be the case, the percentage of failures on positive and negative impulses being 56 and 44, respectively. This is consistent with the findings in Section 3.4.1 that no detectable polarity effect exists with the type of test specimen used.

It is clear from the foregoing that, after the application of a number of impulses of one polarity, the ability of the dielectric

Table 8

EFFECT OF REPEATED STRESSING ON IMPULSE STRENGTH

Paper: P.2

Number of impulses at each level						
	Experiment No.	8	10	10	11	11
	Impregnating compound	C.1	C.1	C.2	C.4	C.4
	Applied gas pressure, lb/in^2 above atmospheric	—	—	—	—	200
1	Number of tests	12	8	8	12	12
	Mean breakdown stress, kV/cm	1 140	1 120	1 090	1 630	1 640
20	Number of tests	12	—	—	—	—
	Mean breakdown stress, kV/cm	1 140	—	—	—	—
200	Number of tests	—	8	8	12	12
	Mean breakdown stress, kV/cm	—	990	970	1 380	1 520

Table 9

EFFECT OF POLARITY REVERSAL ON IMPULSE STRENGTH

Test procedure	Experiment No.	8	12			13
	Paper	P.2	P.2			P.5
	Impregnating compound	C.1	C.1	C.2	C.4	C.1
One impulse at each voltage level	Number of tests	12	10	10	10	12
	Mean breakdown stress, kV/cm	1 140	1 210	1 170	1 530	1 360
10 positive followed by 10 negative impulses at each voltage level	Number of tests	12	10	10	10	12
	Mean breakdown stress, kV/cm	1 010	1 090	1 020	1 240	1 180
10 positive, 10 negative impulses with conditioning pulses between polarity reversals	Number of tests	—	—	—	—	12
	Mean breakdown stress, kV/cm					1 260

to withstand an impulse of the opposite polarity is reduced. This vulnerability to an impulse of reversed polarity is reduced to a certain extent by the application of 'conditioning' pulses between polarity reversals (Experiment No. 13 in Table 9). The procedure adopted was to apply an impulse of 80% of the full amplitude on polarity reversal before proceeding with each group of 10 impulses of the full peak value. In some exploratory tests in which conditioning pulses of 90% of the full value were used, there was a marked tendency for failure to occur on the conditioning pulse, i.e. on polarity reversal accompanied by a decrease in voltage. This provides further strong evidence of the vulnerability of the dielectric to a polarity reversal.

(3.4.4) **Breakdown due to a Single Impulse.**

The reduced ability of impregnated-paper dielectric, after a succession of impulses of one polarity, to withstand an impulse of opposite polarity suggests that, where no reversal of polarity is introduced, the impulse strength may be increased by the preceding surges of the same polarity. This can be tested by comparing the impulse strength obtained by the usual method of applying a series of impulses of increasing amplitude with that given by the application of a single impulse. In order to determine the latter value a sequential procedure is adopted in which a single impulse is applied to each sample, the first sample being subjected to an impulse at the estimated breakdown level. Depending upon whether the first sample fails or withstands the test, the second sample is subjected to a voltage a definite amount lower or higher than that applied to the first sample, and so on. From such a series of tests it is possible to obtain an accurate estimate of the mean single-impulse breakdown strength.

Reference to Fig. 7 shows that the single-impulse breakdown stress is lower than that obtained by the normal procedure by an amount which is approximately half the polarity-reversal effect. It should be noted that the practice of approaching the breakdown strength from a lower level and computing the breakdown stress from the voltage at which failure occurs overestimates the true breakdown strength by an amount which, on an average, is approximately half the percentage step by which the voltage is raised. This consideration does not apply to the breakdown strength obtained by the sequential procedure, and an appropriate correction has been made to the impulse strength obtained by the normal procedure.

Greater accuracy was obtained in experiment No. 15, in which smaller voltage steps were used for both procedures. It will be seen that the results of the two experiments are in close agreement, and analysis of the complete data shows the effect to be highly significant.

(3.5) Electrode Effects

The work discussed in the foregoing Sections has, in the main, been carried out using smooth brass inner electrodes $\frac{3}{8}$ in

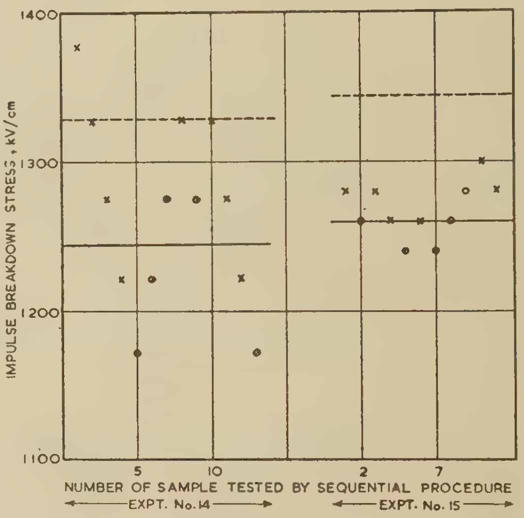

Fig. 7.—The effect of a sequential testing procedure.

Paper: P.5. Impregnant: C.1.

– – – – – Average stress obtained by the use of normal procedure computed from mean values of voltages at highest withstand and at breakdown levels.
——— Average stress obtained by the use of sequential procedure.
× Sample which failed test during sequential procedure.
○ Sample which withstood test during sequential procedure.

in diameter and an outer tinfoil test electrode 2 in long. The effects of using electrode materials other than these, and of variations in outer-electrode length and inner-electrode diameter, are now considered. The effect of introducing a layer of wires on the inner electrode to simulate the stranded conductor of an unscreened cable is also examined.

(3.5.1) **Electrode Material.**

The materials selected for study were those which are commonly used as conductor and sheathing and screening materials in full-sized cables, and for inner and outer electrodes on laboratory models. The effect of each material, as the cathode metal, was assessed by working both with positive and negative polarities. The three types of inner electrode were of copper, aluminium and rhodium-plated brass; the four materials used for the outer-electrode systems were lead and tinfoil, 0·003 in thick, and aluminium and copper foil, 0·002 in thick.

Examination of the data in Tables 10 and 11 shows that the impulse strength is independent of electrode material and, in particular, of the cathode metal. The small differences between the values for the two conductor polarities are not significant. The choice of material for the outer electrode has a considerable influence on the scatter of individual results, the variances being highest for lead and lowest for tin and aluminium. This gives

Table 10

EFFECT OF ELECTRODE MATERIAL ON IMPULSE STRENGTH

Experiment No. 16. *Paper: P.*2. *Impregnant: C.*1

Number of Replicates: 2

Conductor material	Rhodium		Copper		Aluminium		Mean values	
Conductor polarity	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
Outer electrode material:	kV/cm	kV/cm	kV/cm	kV/cm	kV/cm	kV/cm	kV/cm	kV/cm
Lead	1 060	1 120	1 040	1 000	1 050	1 200	1 050	1 110
Tin	1 040	1 050	1 040	1 110	1 080	1 030	1 055	1 060
Aluminium	1 010	1 050	1 020	1 090	1 040	1 060	1 025	1 070
Copper..	1 070	1 110	1 100	1 080	1 020	1 210	1 060	1 150

some justification for the use of tinfoil, as opposed to lead or copper foil, for tests on laboratory models.

(3.5.2) **Electrode Length.**

It is possible, with certain assumptions, to predict theoretically the magnitude of the variation of electric strength with electrode area using methods drawn from the statistical theory of extreme values.[9,10] The theoretical treatment, based upon the assumption that the variance of results with a given electrode area is entirely due to the distribution of flaws in, or non-homogeneity of, the dielectric, relates the variation of electric strength with electrode area to the total variance. In practice, however, factors which are independent of electrode area, such as unwanted variations in the construction and processing of samples and errors in high-voltage measurement, contribute to the variance. Thus the theory would be expected to give a slight over-estimate of the actual variation of impulse strength with electrode area.

The results of an experimental investigation of the electrode-area effect made by variation of the length of the outer electrode from 1 in to 16 in are given in Fig. 8. The statistical analysis

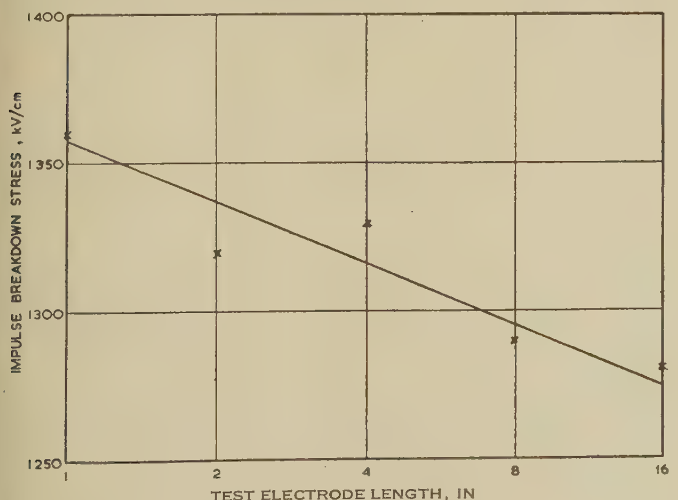

Fig. 8.—The variation of impulse strength with electrode area.

Experiment No. 17.
Paper: P.5.
Impregnant: C.1.
Number of replicates: 8.

shows that there is a significant linear relationship between impulse strength and the logarithm of the electrode length, the breakdown strength decreasing by 2% as the electrode length is doubled. This compares with a theoretical figure of nearly 3% based on the mean coefficient of variation of 5·5%. The experimental slope is not significantly lower than the theoretical slope

Table 11

EFFECT OF CATHODE MATERIAL ON IMPULSE STRENGTH

Experiment No. 16. *Paper: P.*2

*Impregnant: C.*1

Cathode metal	Number of tests	Mean impulse breakdown stress
		kV/cm
Aluminium	14	1 080
Copper	14	1 065
Rhodium	8	1 080
Lead	6	1 050
Tin	6	1 050

of the regression lines, but possible reasons for it being so have been indicated above. The proportion of failures at the edge of the outer test electrode, which occurred in only four of the tests made, showed no tendency to increase with the shorter electrode lengths. Samples constructed with four 4 in test electrodes abutting each other gave a mean impulse strength which was not detectably different from that of the samples with a single 16 in test electrode. It is therefore considered that the measured effect of electrode area was not subjected to a spurious decrease due to greater edge effects with the shorter electrode lengths or to an increase caused by greater difficulty of application of the longer electrodes.

(3.5.3) **Conductor Diameter.**

The variation of the impulse strength of lapped impregnated-paper dielectric with the diameter of the inner electrode has been studied using conductor diameters of $\frac{5}{16}$ in and $\frac{5}{8}$ in. The results given in Table 12, obtained with a dielectric wall thickness of approximately 25 mils and a low-viscosity impregnant, show that the impulse strength for the smaller conductor is significantly greater by about 10%. In experiment No. 18, in order to obtain

Table 12

EFFECT OF CONDUCTOR DIAMETER ON IMPULSE STRENGTH

*Paper: P.*2. *Impregnant: C.*1

Conductor diameter	Experiment No.	9	18	
	Paper-tape width, in	17/32	3/8	3/4
	Butt-gap width, in	1/32	1/16	1/16
$\frac{5}{16}$ in	Number of tests	18	8	8
	Mean breakdown stress, kV/cm	1 250	1 200	1 230
$\frac{5}{8}$ in	Number of tests	9	8	8
	Mean breakdown stress, kV/cm	1 130	1 130	1 090

a comparison between the two conductor diameters with the same angle of lay of the paper tapes, two paper-tape widths were used. It is seen, however, that paper-tape width and angle of lay are without detectable effect on impulse strength.

The data given in Table 13 show a similar variation of impulse strength with conductor diameter with a dielectric thickness of approximately 60 mils. Reference to Table 5 shows that the impulse strength of dielectrics having a viscous impregnant is influenced by conductor diameter to a similar extent. Variation of the butt-gap width between zero and $\frac{1}{8}$ in does not significantly affect the relationship between impulse strength and conductor diameter (see Fig. 5).

Table 13

EFFECTS OF CONDUCTOR STRANDING AND CONDUCTOR DIAMETER ON IMPULSE STRENGTH

Experiment No. 20. *Paper: P.*5. *Impregnant: C.*1

Conductor diameter	Type of conductor	Smooth	Stranded
in			
0·313	Number of tests	4	—
	Mean breakdown stress, kV/cm	1 420	—
0·40	Number of tests	4	4
	Mean breakdown stress, kV/cm	1 360	1 380
0·625	Number of tests	4	—
	Mean breakdown stress, kV/cm	1 280	—
0·78	Number of tests	4	4
	Mean breakdown stress, kV/cm	1 250	1 240

The possibility that dependence of impulse strength upon conductor diameter is ascribable to changes in electrode area is not fully supported, as the data in the previous Section show that this accounts for only a small proportion of the observed effect. A doubling of the conductor diameter, i.e. a doubling of the effective electrode area, would be expected to produce a decrease of about 2% in impulse strength, using the considerations of the previous Section. This is clearly much less than the difference in Table 12, and even after appropriate allowance has been made for the change in electrode area, the residual effect associated with diameter remains significant.

(3.5.4) Conductor Stranding.

The effect of the use of a stranded inner electrode upon impulse strength is shown in Table 13. In this Table the impulse strengths with smooth conductors are compared with those of stranded conductors having the same overall diameter. For both conductor sizes studied the impulse strengths with strands are not significantly different from those for the corresponding smooth conductors.

For these particular sizes of cable model the theoretical increase in maximum stress introduced by stranding is of the order of 20%, based upon the work of Levi-Civita[11] and others. It must therefore be concluded that the theoretically derived 'stranding factor', which is often used, is not appropriate in estimating impulse breakdown strength.

The mean impulse breakdown stress of 1 280 kV/cm given by the samples with 0·625 in-diameter smooth conductors is of the same order as that obtained with the same combination of oil and paper in Section 3.1, i.e. 1 320 kV/cm. These two values were obtained with dielectric wall thicknesses of approximately 60 and 25 mils, and outer-electrode lengths of 4 in and 2 in, respectively. After correcting for the effect of the different electrode lengths it is evident that impulse strength is virtually independent of dielectric wall thickness over the range considered in the paper.

(3.6) General Observations on Breakdown Paths

Careful examination of all the specimens after the electrical breakdown tests revealed that almost invariably failure occurred in the region under the outer test electrode. In general, in over 80% of the samples examined the site of failure was not associated with the edges of the test electrode, the inclusion of the results in which edge failure had occurred not significantly affecting the mean breakdown voltage for a group. This indicates the efficiency of the guard system employed, in reducing stress concentration at the edges. There was a slightly greater tendency for edge failures to occur with higher-viscosity impregnants and in those cases in which reversals of polarity were introduced in the testing procedure.

All failures were of the radial type with very little tendency for longitudinal tracking to occur. With the thicker dielectric walls used on the 2 ft models the breakdown started as a small radial hole from the conductor, but in a number of cases it became diffuse in the outer layers with extensive charring and tearing of the papers. The breakdown paths showed a strong preference for the butt gaps, but were not necessarily associated with those in the layer of paper adjacent to the conductor. With the 50/50 registration generally used, the puncture nearly always traversed alternate oil spaces and paper tapes.

In a very few instances with a high-viscosity impregnant (C.4) the failure avoided the butt gaps completely.

Examination of a number of samples of lapped impregnated condenser tissue after impulse breakdown tests showed that, as well as the normal radial puncture, general blackening of the edges of the paper tapes in the oil channels had occurred. Tests between plane brass electrodes on single sheets of impregnated cable paper, with slots to simulate butt spaces, revealed that impulse breakdown occurred almost exclusively at the oil/paper interface in the radial direction.

(4) DISCUSSION

The observations in the previous Section strongly indicate that the oil-filled butt spaces in a lapped dielectric constitute points of weakness with which impulse failure is associated. The variation of impulse strength with paper thickness, ascribable to consequent changes in butt-gap depth rather than to paper thickness itself, and the effect of butt-gap width, both show that the butt gap is effective not only in determining the site of failure but also in partially affecting the breakdown stress of the whole dielectric.

The view has been expressed[6] that the impulse strength of this type of dielectric is determined, not partially but wholly, by the breakdown strength of the compound in the butt spaces. If this were true, an increase of paper density (and hence permittivity) would decrease the breakdown strength of the whole dielectric, because of the resulting increase in the stress upon the oil in the butt gap. Again, the stress in the butt gap depends upon the registration used, and is least when the latter is 50/50; so that the above view would lead to a decrease of the breakdown strength of the whole dielectric with a change of registration from 50/50 to 65/35. In both of these cases, however, the observed effects of density and registration are in senses opposite to those required by the above hypothesis, which must therefore be rejected.

From the relationship between impulse strength and paper density, impermeability and uniformity, it must be inferred that while the butt gap locates the site of failure and partially determines the breakdown strength of the whole dielectric, the latter is also dependent upon the physical properties of the paper in series with the butt gap. The foregoing reasoning applies with greater force to dielectric impregnated with a low-viscosity oil, for which the effect of paper density is more marked than for a

high-viscosity impregnant. For this type of dielectric the experimental results given in Section 3.1 enable good estimates to be made of the effects of paper thickness, density, impermeability and uniformity.

The independence of applied gas pressure on the impulse strength of fully impregnated paper dielectric (Section 3.3.2) indicates that, with a relatively small number of applied impulses, gaseous ionization plays no part in the breakdown process. On the other hand, if gaseous cavities of sufficient size are deliberately introduced by a draining process, a very marked lowering of breakdown strength occurs, and the impulse strength becomes highly pressure-dependent.

Since the reduction of impulse strength caused by repeated application of impulse voltages near the breakdown level (Section 3.4.2) is considerably greater at atmospheric pressure than at 200 lb/in^2, the effect is considered to be due to the formation or growth of gaseous cavities. Moreover, gas bubbles have actually been observed, at atmospheric pressure, in sheets of impregnated paper between flat electrodes when subjected to a large number of impulses just below the breakdown level.

The higher impulse strength found with impulses of the same polarity of increasing amplitude (the normal procedure) as compared with the 'single impulse' value, and the reduction in strength with polarity reversal, suggest that a space charge or interfacial polarization, which tends to oppose the applied field, is set up in the dielectric by the application of impulses of one polarity. A similar explanation has been put forward previously[12] to account for a polarity-reversal effect when testing oil-impregnated pressboard with direct voltages.

The increase in impulse strength which can be achieved, when testing with 10-positive-10-negative impulses, by the application at the reversal of polarity of an impulse of about 80% of the full value can then be ascribed to neutralization of the charges, thus making the first impulse of full value after reversal less onerous.

The breakdown strength due to a single impulse is shown in Section 3.4.4 to be significantly lower than that given by the usual procedure by an amount which is approximately half the polarity-reversal effect. This is consistent with the postulated mechanism.

The observed variation of impulse strength with electrode area is sufficient to account for only a small part of the change of impulse strength with conductor diameter. A reduction in the conductor diameter not only leads to a reduction in electrode area, but also gives rise to an electric field in which the stress falls away more rapidly from the conductor. It may be, therefore, that a dielectric-volume effect is at least partially responsible for the variation of impulse strength with conductor diameter, although direct evidence of this is lacking.

The theoretical calculation of the increase in maximum stress with a stranded, as compared with a smooth, conductor is based upon the initial stress distribution in the dielectric. However, at stresses approaching the impulse failure level, local breakdown of the oil in highly stressed regions is considered to occur, which will modify the initial stress distribution considerably. This may be why any effect of stranding upon impulse strength is much less than that predicted by the theoretically derived stranding factor.

(5) CONCLUSIONS

Using cable models of fully impregnated lapped paper dielectric, the following properties of the impulse strength have been shown experimentally:

(i) It decreases with increasing paper-tape thickness. For both high- and low-viscosity impregnants with paper of 7·5 mils nominal thickness, the strength is about 25% lower than with 1·5-mil paper.

(ii) It increases with paper density, more markedly with low- than with high-viscosity impregnants. With the former, the strength increases by approximately 25% as the apparent density is increased from 0·7 to 1·2 g/cm^3, or alternatively,

(iii) It increases with increasing paper impermeability and uniformity. These two factors are considered, in relation to impulse strength, more fundamental than density.

(iv) It increases with decreasing butt-gap width, and is lower by about 20% with 50/50 than with 65/35 or 75/25 registration.

(v) It increases with increasing compound viscosity; this effect accounts for the variation of impulse strength with temperature. For the more viscous compounds the strength decreases by about 20–30% with increasing temperature over the range of normal cable operating temperatures, depending upon the type of paper used.

(vi) It is independent of applied gas pressure (though drained dielectrics have an impulse strength which increases markedly with increasing gas pressure).

(vii) It is independent of the polarity of the impulse wave applied to the conductor for the particular models used, in which the electric field is much less non-uniform than in full-sized cables.

(viii) It decreases with increase in the number of impulses applied prior to breakdown, with the normal testing procedure.

(ix) It is reduced with tests involving reversals of polarity, by about 12% with a low-viscosity impregnant and by about 20% with a high-viscosity impregnant.

(x) It increases with decreasing conductor diameter.

(xi) It increases with decreasing electrode area, but this effect only accounts for a small proportion of the observed increase with decreasing conductor diameter.

(xii) It is substantially independent of the electrode metal.

(xiii) It is dependent upon stranding to a much smaller extent than that expected from the theoretical stress distribution.

In the light of the above results, it is concluded that the impulse failure of a lapped dielectric is initiated at or in the region of the butt spaces, probably at the radial oil/paper interface, and may possibly be considered as a two-phase process—failure of the butt gap (by itself not necessarily leading to complete breakdown), and failure of the impregnated paper in series with the butt gap. Both phases influence the level at which complete failure takes place.

(6) ACKNOWLEDGMENTS

The authors' thanks are due to Dr. L. G. Brazier, Director of Research and Education, British Insulated Callender's Cables, Ltd., for permission to publish the paper.

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(8) APPENDIX: ANALYSIS OF A TYPICAL STATISTICALLY DESIGNED EXPERIMENT (EXPERIMENT No. 12)

(8.1) Factors Investigated

The experiment was designed to compare the impulse strengths under the two test conditions

(*a*) Single negative impulses at each level.
(*b*) Ten positive followed by ten negative impulses at each level.

It was thought that the magnitude of any possible difference might be dependent upon viscosity, and hence three impregnating compounds were used; two (oils C.1 and C.2) were of low viscosity and one (oil C.4) was of high viscosity. Thus there were two factors—one involving two test procedures, and the other, three compounds, making in all six treatments.

(8.2) Experimental Design[13]

It was convenient, experimentally, to process in blocks of four samples per day. A balanced incomplete block design was therefore used, consisting of ten replications of each of the six treatments arranged in 15 blocks of four samples, so that any two treatments occurred together in six blocks. The design enabled any significant block-to-block (i.e. day-to-day) variations to be eliminated from the comparisons between treatments. Further, for the purpose of deciding the order of experimentation, the blocks were divided into groups of three, each treatment occurring twice in each trio of blocks. These five groups were randomized, as also were the blocks within groups and treatments within blocks.

(8.3) Analysis

There is usually more than one way of analysing a balanced incomplete block experiment, according to which comparisons are of most interest. In this particular case, the first test made was to determine whether, in fact, there were significant day-to-day variations in impulse strength. To do this, block totals were first adjusted for the treatments they contained; then the ratio of the mean square, corresponding to these adjusted totals, to that corresponding to the residual (experimental) error, was tested for significance. This ratio was found to be non-significant, although occasionally in other experiments significant day-to-day variations in impulse strength have occurred.

This meant that there would be no advantage in adjusting the treatment totals according to the blocks in which they occurred. The division into blocks was therefore ignored, and the division into groups of three days was retained in the second stage of the analysis of variance, which then appeared as in Table 14.

Table 14.—Analysis of Variance of Impulse Breakdown Stress (kV/cm × 10^{-1})

Source of variation	Degrees of freedom	Sum of squares	Mean square	Mean square ratio	Significance
(i) Groups of days	4	29	7	0·1	N.S.
Treatments:	(5)	(15 755)			
(ii) Test Procedure, T.	1	5 434	5 434	65	V.H.S.
Compounds:					
(iii) C_1 (high *v.* low viscosity)	1	9 310	9 310	112	V.H.S.
(iv) C_2 (between low viscosity compounds)	1	297	297	3·6	N.S.
Interactions:					
(v) $C_1 \times T$	1	686	686	8·3	H.S.
(vi) $C_2 \times T$	1	27	27	0·3	N.S.
(vii) Residual	50	4 158	83		

N.S. Not significant.
S. Significant between the 5% and 1% levels.
H.S. Significant between the 1% and 0·1% levels.
V.H.S. Significant beyond the 0·1% level.

The comparison between treatments could then be considered as between compounds, between test procedures, and as the interaction of these two factors. Further subdivisions are possible within compounds, and of the interactions, comparison being made between low- versus high-viscosity (C_1 and $C_1 \times T$) and between the two low viscosity compounds (C_2 and $C_2 \times T$).

All the appropriate mean squares were tested against the residual mean square [line (vii) Table 14] which is a measure of the experimental error. Significance levels are indicated in the last column of the Table.

(8.4) Discussion of the Analysis

The residual mean square [line (vii)] is 83, which corresponds to a standard deviation of 91 kV/cm ($\equiv 7{\cdot}5\%$ of the grand mean).

The significance of the ratios of the mean squares in lines (ii) and (iii) shows that the test procedure, T, and viscosity of impregnating compound C_1, both have an effect on the breakdown strength, but it will be seen from line (v) that the magnitude of the effect of the test procedure depends upon the viscosity of the compound. Lines (iv) and (vi) show that there is no evidence of any difference in behaviour between the two low-viscosity compounds C.1 and C.2.

[The discussion on the above paper will be found on page 589.]

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Apr. 1956

BREAKDOWN UNDER IMPULSE VOLTAGES OF SOLID AND LIQUID DIELECTRICS IN COMBINATION

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SUMMARY

The progress of an investigation of the breakdown of solid and liquid dielectrics in combination is described, and generalizations are made about the effects of electrode shape, impulse duration and polarity on the puncture voltage of alternate layers of solid and liquid, and on the flashover voltage of a solid and liquid interface under various conditions of stress.

(1) INTRODUCTION

The paper describes the results so far obtained in a study of the factors affecting the impulse breakdown of solid and liquid dielectrics in combination. The aim of the investigation is to formulate generalizations which will be of use to designers of electrical equipment.

Breakdown in electrical equipment containing solid and liquid dielectrics usually begins with discharges in the liquid. These may lead to complete breakdown between electrodes by a flash-over path passing over the surface of the solid insulation, or by a puncture path penetrating through the solid insulation. In the second case the breakdown voltage is lower than would be required if puncture of the solid were not preceded by breakdown in the liquid.

To avoid the dependence of results on too many variables, and to increase the chance of formulating generalizations from a reasonable amount of work, the simplest geometrical arrangements of electrode and insulation have been used which seemed suitable for studying independently puncture through the solid material and flashover along the solid–liquid interface.

Most of the data given deal with puncture of single sheets of pressboard and of assemblies of pressboard sheets separated by oil gaps, and with flashover of pressboard surfaces with and without a large component of stress normal to the surface. Some results are given on synthetic-resin-bonded paper. The test samples were immersed in transformer oil.

In order to make progress as rapidly as possible the effects of shape and dimensions of electrodes and solid insulation, and the effects of voltage duration and polarity, have been investigated at room temperature. There seems no reason to doubt that the variables mentioned would produce similar effects at other temperatures. The puncture of single sheets has also been studied at 90° C.

(2) EXPERIMENTAL PROCEDURE

Impulse voltages of waveshape 1/5 or 1/50 microsec were applied to the test sample. Unless the effect of repeated impulses was being studied the voltage was raised about 5% after each application until breakdown occurred. The effect of a previous impulse just below the breakdown voltage appeared to be negligible, so that the voltage required for breakdown with a single application was obtained.

To examine the effect of repeated impulses some tests were made in which applications were repeated at one voltage until breakdown occurred or 1 000 impulses had been applied, but the best method of obtaining the voltage required to cause breakdown in N applications appeared to be to apply N impulses at each of a number of successive voltages increasing in 5% steps until breakdown occurred—a value of $N = 500$ was used at low voltages and $N = 100$ at higher voltages.

Ten samples were normally tested to obtain the breakdown voltage for any one set of conditions. With the exception of point P in Fig. 2 and three points in Fig. 7, any figure quoted or plotted represents the mean of ten or more observations.

(3) CONSISTENCY OF OBSERVATIONS

The coefficient of variation in a group of ten observations was, on the average, 9%. The lowest observation in a group of ten was occasionally 30% below the mean.

It is considered that the mean figure derived from a group of ten observations is significant to about 10%, and that discrepancies of this magnitude do not invalidate curves drawn or generalizations made.

(4) PREPARATION OF MATERIAL

Synthetic-resin-bonded paper sheets and tubes were not treated in any special way but were stored in the laboratory under ordinary atmospheric conditions before test.

Pressboard sheets and tubes were dried under vacuum at a temperature of 100° C and a pressure of 0·05 mm Hg or less, and impregnated with transformer oil at a temperature of 100° C and a pressure of about 0·1 mm Hg. After admission of the vacuum-dried oil the impregnating chamber was allowed to cool down. When removed from the impregnating tank the pressboard was immediately immersed in oil in a storage tank. In the preparation of the most elaborate test samples the material was exposed to air for about one minute, but all components were swamped in oil and care was taken to exclude air from the assembly.

A few puncture tests were made on 6·4 mm pressboard sheets, dried and impregnated at atmospheric pressure.

(5) BREAKDOWN BY PUNCTURE

(5.1) Effect of Vacuum Impregnation

The results of tests on sheets impregnated at atmospheric pressure in accordance with B.S. 231, together with comparable figures for vacuum-impregnated sheets, are given in Table 1.

The results indicate that impregnation of pressboard is possible without vacuum treatment if sufficient time is allowed, but that the 48 hours' immersion specified in B.S. 231 is insufficient for complete impregnation of 6·4 mm sheets.

(5.2) Puncture Voltage of Solid Sheets, and of Sheets separated by Oil Gaps

Puncture tests were made on single sheets of pressboard and of phenolformaldehyde-resin-bonded paper containing 50% resin, with one electrode a plane and the other a sphere of 50 mm

The paper is an official communication from the National Physical Laboratory.

Table 1

IMPULSE PUNCTURE VOLTAGE (1/50 MICROSEC WAVES) OF 6·4 MM PRESSBOARD SHEETS

Impregnation pressure	Number of days' immersion in oil at 90° C	Puncture voltage	
		at 20° C	at 90° C
		kV	kV
Atmospheric ..	2	420	280
Atmospheric ..	60		350
Vacuum		425	350

diameter or a sharp-edged cylinder. The results given in Table 2 were independent of electrode shape or polarity, of voltage duration in the range from 1/5 to 1/50 microsec impulses, and of the pressure between electrode and dielectric surfaces, provided that the surfaces were in contact and the dielectric sheet was undamaged by the electrode.

Table 2

IMPULSE PUNCTURE VOLTAGE OF SINGLE SHEETS

Thickness	Puncture voltage			
	Pressboard		Phenol-resin-bonded paper	
	at 20° C	at 90° C	at 20° C	at 90° C
mm	kV	kV	kV	kV
0·75			72	72
1·6	155	155	140	
6·4	425	350	450	450

The relation between puncture voltage and electrode separation was determined for several arrangements of pressboard sheets; the arrangements differed in number and/or thickness of sheets. The outer sheets were in contact with the electrodes. To control separation between three or more sheets it was found necessary to insert pressboard packing, which was placed with one edge passing through the axis of the electrodes (see Fig. 1). With

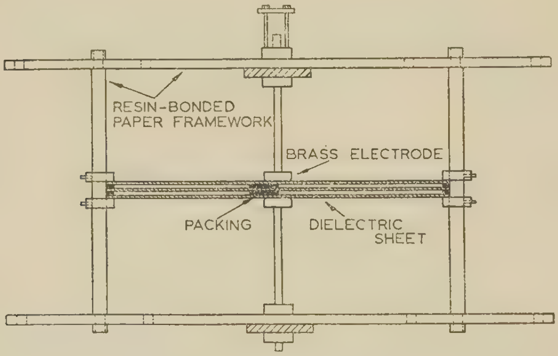


Fig. 1.—Framework for testing assemblies of dielectric sheets in oil.

two sheets, measurements were made with and without packing. Cylindrical electrodes 76 mm in diameter with a 3 mm edge radius were used.

The results for sheets 1·6 and 6·4 mm thick are given in Fig. 2, and those for 3·2 mm sheets in Fig. 3. The four approximately parallel full lines in Fig. 2, which refer to arrangements of 2, 3, 4 and 5 sheets of 1·6 mm pressboard with packing between the sheets, using 1/50 microsec impulses, provide a consistent

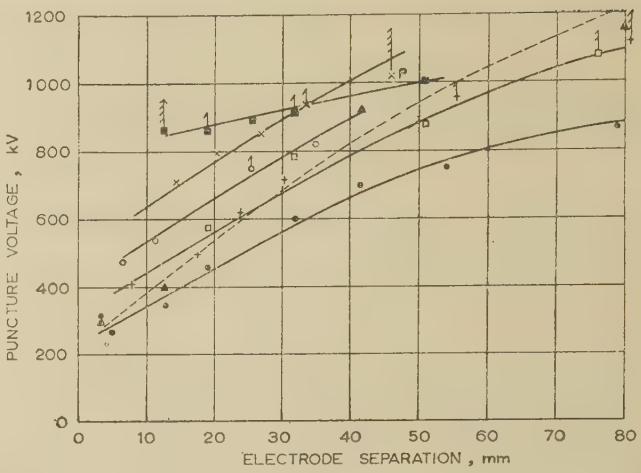


Fig. 2.—Puncture voltage of alternate layers of 1·6 and 6·4 mm pressboard and transformer oil.

Flashover on one sample.
Flashover on five samples.
● + ○ × Two, three, four and five sheets, respectively, 1·6 mm thick with packing, 1/50 microsec wave.
■ Two sheets 6·4 mm thick with packing, 1/50 microsec wave.
□ Two sheets 1·6 mm thick without packing, 1/50 microsec wave.
▲ Two sheets 1·6 mm thick, with packing, 1/5 microsec wave.
P Mean of six observations.

family of curves within about 5% of all the observations except one. These curves have an initial slope of about 12 kV/mm and are approximately linear for electrode separations up to 30 or 40 mm. The observations on 3·2 mm sheets (Fig. 3) are less

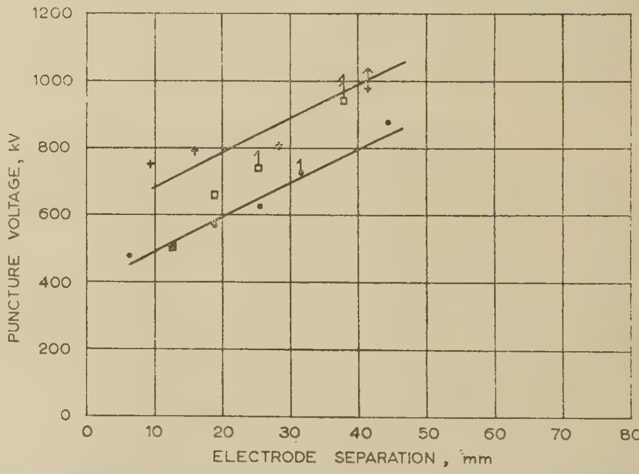


Fig. 3.—Puncture voltage of alternate layers of 3·2 mm pressboard and transformer oil, 1/50 microsec waves.

Flashover on one sample.
Flashover on five samples.
● Two sheets with packing.
+ Three sheets with packing.
□ Two sheets without packing.

consistent, but can be represented to within 10% by parallel lines having a slope of 10 kV/mm. The slope for two 6·4 mm sheets (full line through solid squares in Fig. 2) is about 4 kV/mm. Puncture observations on three 6·4 mm sheets were prevented by flashover. Observations on two sheets without packing between are shown by open squares in Figs. 2 and 3, while observations on two 1·6 mm sheets with 1/5 microsec impulses are shown by solid triangles and a dashed line in Fig. 2.

Further tests on two 1·6 mm sheets at an electrode separation of 54 mm were made with a spherical electrode of 76 mm radius and with a sharp-edged cylinder 40 mm in diameter, the other electrode in each case being a plane. The mean puncture voltages

were 740 and 750 kV. The puncture voltage of a similar arrangement using a sharp-edged electrode and a plane and reversing the polarity of the applied impulse after every shot was 730 kV. These results agree closely with the value plotted in Fig. 2.

Puncture was preceded by surface discharges, which might conceivably produce deterioration of the dielectric, and some tests were therefore made with repeated applications. The '500 shot' puncture voltage of 6·4 mm and 1 mm pressboard sheets with a sharp-edged high-voltage electrode of either polarity was about 15% below the 'single shot' value. With polarity changed after each shot, or with damped oscillatory impulses having a period of 9 microsec and falling to half value in 30 microsec, the 500-shot value was about 25% below the single-shot value. The 100-shot puncture voltage of two 1·6 mm sheets for an electrode separation of 54 mm was measured with positive, with negative, and with alternate positive and negative impulses, and the results were, respectively, 20%, 15% and 25% below the single-shot value of 750 kV.

The breakdown voltage of oil alone is dependent on electrode shape, as shown in Fig. 4. The oil was periodically cleaned

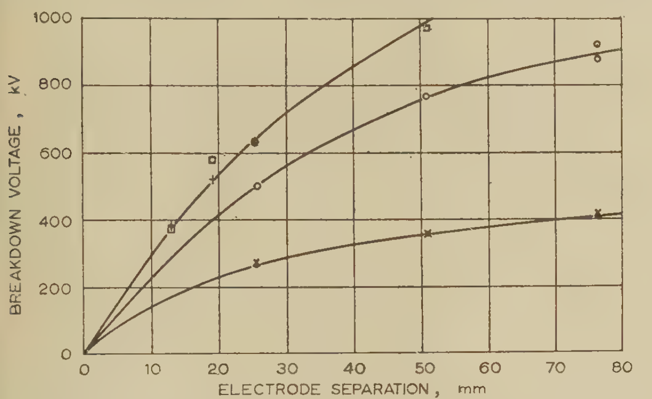


Fig. 4.—Breakdown voltage of oil with 1/50 microsec waves.

× Positive ● Negative; h.v. electrode sharp-edged.
○ H.V. electrode edge, 3 mm radius.
□ H.V. electrode, 76 mm radius; before cleaning oil.
+ H.V. electrode, 76 mm radius; after cleaning oil.

during the investigation. Before cleaning, the breakdown voltage in the standard 4 mm gap (B.S. 148) was about 30 kV (r.m.s.) and the resistivity about 4×10^{12} ohm-cm. After cleaning, the figures obtained were 50 or 60 kV (r.m.s.) and about 20×10^{12} ohm-cm measured at room temperature. The impulse breakdown voltage of the oil was not affected by cleaning, so that presumably the oil can be considered to have been sufficiently uniform in condition throughout the tests for all the results to be strictly comparable in relation to other variables.

Effect of Thickness of Solid Dielectric.—The results on single sheets (Table 2) and on sheets in contact with each other (minimum possible spacing for arrangements referred to in Figs. 2 and 3) suggest that, for N sheets of thickness t, the puncture voltage of pressboard between electrodes spaced Nt apart is roughly proportional to $N^{0 \cdot 9} \times t^{0 \cdot 8}$. For two or more sheets separated by oil the puncture voltage increases with oil gap at a rate which is greater for thin than for thick sheets.

Effect of Packing.—Packing reduces the puncture voltage. However, in any practical equipment, packing is likely to be necessary for mechanical reasons, so that arrangements without packing are of doubtful interest.

Effect of Electrode Shape.—The puncture voltage of solid dielectric sheets, or of alternate layers of pressboard and transformer oil with the outer sheets in contact with the electrodes, appears to be independent of the shape of the electrodes.

Effect of Polarity.—Independence of electrode shape implies independence of polarity.

Effect of Repeated Impulses.—The 100-shot puncture voltage with impulses of one polarity is about 15% below the single-shot value. With impulses of alternate polarity the reduction is about 25%. (The difference between the 100-shot and 500-shot puncture voltages is likely to be small, so that the figures given for single sheets and two sheets with oil between are in good agreement.)

Effect of Voltage Duration.—The dashed line in Fig. 2 shows that the puncture voltage of two 1·6 mm sheets is not affected by voltage duration at small spacings but is some 30% higher for 1/5 than for 1/50 microsec waves at large spacings. This is consistent with time lags observed with 1/50 microsec waves, which were of the order of a microsecond at small spacings and up to 50 microsec at large spacings.

(5.3) Discharges preceding Breakdown

Discharges radiating from the electrodes along the solid surfaces began at a voltage below that required for puncture. These discharges left permanent marks on the dielectric surface, and the cumulative damage caused by a large number of repetitions is presumably responsible for the reduction of puncture voltage previously described in Section 5.2.

For repeated impulses of one polarity, subsequent discharges were shorter than the first. With reversal of polarity at each application, the discharges did not decrease in length. On removal of the solid sheet from the oil a layer of oil adhered to that part of the surface which had been in the neighbourhood of the electrode, and sparks could be obtained between this layer and an earthed conductor, thus demonstrating the presence of a residual charge on the dielectric surface. This charge would be of the polarity of the applied impulse and would reduce the local field at the electrode arising from a succeeding impulse of the same polarity. This may account for the observed reduction in the severity of the discharge.

The length of the discharge depends on the duration of the impulse voltage, and is greater for 1/50 than 1/5 microsec waves. The rate of change of voltage also affects the phenomenon, and it is possible to apply a direct voltage gradually without visible discharges and to obtain discharges on suddenly removing the voltage.

(5.4) Mechanism of Breakdown

Breakdown begins with the discharges from the electrodes described above. These discharges will, to some extent, convert any electrode into a plane electrode, the effect being limited by the voltage drop in the discharge. This seems to explain why the puncture voltage does not depend on electrode shape.

In tests without packing between the sheets the inner surfaces, i.e. the surfaces bounding the oil gap or gaps, were only slightly marked except at the point of puncture. On samples which flashed over without puncture the only damage on the inner surfaces consisted of a few faint marks radiating from one or more points. This suggests that the second step in the breakdown process starts in the oil between the sheets and that when a breakdown channel reaches a sheet it leads to surface discharges similar, though on a smaller scale, to those from an electrode.

In tests with packing between the sheets the inner surfaces were only slightly marked and the packing surfaces unmarked. Puncture nearly always occurred at the edge of the packing, so that the packing surface is a point of weakness, and it is concluded that the second stage in the breakdown process takes place in the oil along the surface of the packing.

When the oil gap is completely bridged by a relatively conducting channel, practically all the voltage will be applied to the solid dielectric, and for a total solid thickness of the order of 1 cm, puncture will rapidly follow. To consider the breakdown process as consisting of three consecutive independent processes—surface discharges from the electrodes, bridging of the oil gap by an ionized channel, and puncture of the solid sheets—is no doubt an oversimplification, since all the processes involve time and will be interrelated.

At large spacings, however, it seems probable that the time to breakdown is chiefly dependent on the oil gap. As a conducting channel extends through the oil, the voltage gradient in the oil at the head of the channel becomes stronger and propagation of the channel becomes faster. If the channel meets a barrier of solid dielectric, discharges will spread over the surface of this, making the field beyond the barrier more uniform. For a given electrode separation, the time required for breakdown of all the oil gaps can therefore be expected to decrease as the average voltage gradient between the electrodes increases, and to increase as the oil gap is subdivided. Experimental observations of breakdown times with 1/50 microsec impulses given in Table 3 confirm this conclusion.

Table 3

TIME LAG TO PUNCTURE OF SOME ASSEMBLIES WITH 1/50 MICROSEC IMPULSES

Total gap	Pressboard sheets		Mean gradient	Number of oil gaps	Mean time lag
	Number	Thickness			
mm		mm	kV/cm		microsec
50	2	6·4	200	1	3
54	2	1·6	137	1	28
56	3	1·6	170	2	18
35	4	1·6	235	3	14
46	5	1·6	220	4	one observation only (52)

From the data given in Fig. 2 and Table 3 some indication of the effect of impulse duration may be derived in particular cases. For example, a gap of 50 mm may be designed to have an average breakdown voltage of 1 MV if two 6·4 mm sheets or four 1·6 mm sheets are used. With 1/5 microsec waves the puncture voltage seems likely to be appreciably higher than with 1/50 microsec waves in the second case but not in the first.

(6) BREAKDOWN BY FLASHOVER

(6.1) Flashover under Tangential Stress

Surface flashover under tangential stress was investigated on dielectric tubes from 13 to 250 mm in internal diameter and from 1·5 to 13 mm in wall thickness. The electrodes were mounted coaxially on the tubes as shown in Fig. 5(*a*). The radial dimension *h* of the electrodes varied from 0·1 to 230 mm.

The flashover voltage between 0·1 mm foil electrodes on pressboard tubes with 1/50 microsec waves is shown by the full line in Fig. 6. The dashed line indicates the results for electrodes of which the radial thickness [*h* in Fig. 5(*a*)] exceeds the electrode separation. The dotted line shows the flashover voltage between foil electrodes with 1/5 microsec waves. The full and dashed lines in Fig. 6 represent extremes. Electrodes of intermediate thickness have intermediate values as illustrated by the points plotted in Fig. 6 for 10 mm electrodes—the value plotted at 1 150 mm represents a lower limit rather than the surface flashover voltage, since the breakdown path was not entirely along the surface but ended on the outer edge of one electrode. With

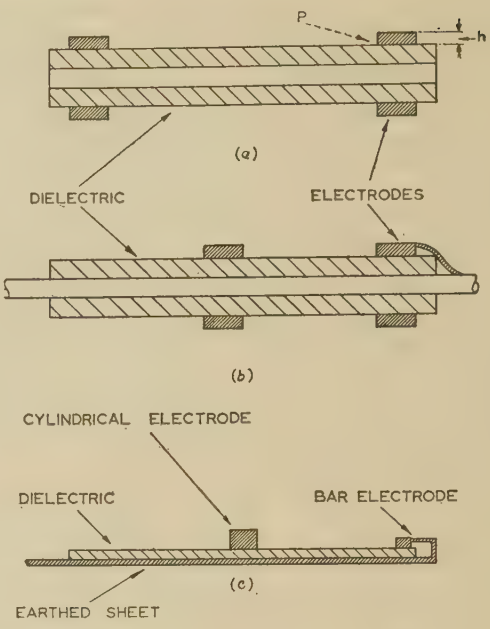


Fig. 5.—Samples for flashover tests.
(*a*) Tubular sample for flashover under tangential stress.
(*b*) Tubular sample for flashover under normal and tangential stress.
(*c*) Sheet sample for flashover under normal and tangential stress.

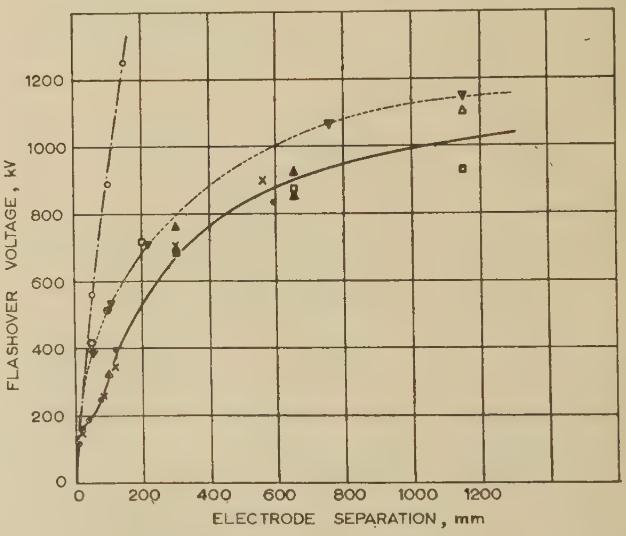


Fig. 6.—Flashover voltage between electrodes mounted on pressboard tubes.
△ 13 mm inner-diameter 3 mm-wall, foil electrodes, 1/50 microsec wave.
● 13 mm inner-diameter 1·5 mm wall, foil electrodes, 1/50 microsec wave.
× 254 mm inner-diameter 3 mm-wall, foil electrodes 1/50 microsec wave.
■ 13 mm inner-diameter 13 mm-wall, foil electrodes, 1/50 microsec wave.
○ 13 mm-inner-diameter 3 mm-wall, 48 cm-diameter disc electrodes, 1/50 microsec wave.
□ 13 mm-inner-diameter 3 mm-wall, 1 cm-thick electrodes, 1/50 microsec wave.
+ 13 mm-inner-diameter 3 mm-wall, 1 cm-thick electrodes, alternate polarity 1/50 microsec wave.
▲ 13 mm-inner-diameter 3 mm-wall, foil electrodes, alternate polarity, 1/50 microsec wave.
▼ 13 mm-inner-diameter 3 mm-wall, foil electrodes, 1/5 microsec wave.

this exception, all these flashovers occurred on the pressboard surface and damaged it to some extent. The upper triangular point in Fig. 6 at 650 mm spacing with foil electrodes was obtained after removing the outer layers from the tubes used to obtain the lower point.

Some tests were made with disc electrodes, 480 mm in diameter, with the edge in contact with the tube [P in Fig. 5(*a*)] rounded. With a 40 mm radius, the breakdown voltages of gaps

of 50 and 100 mm were 680 and 1 130 kV, all breakdowns at 50 mm being through the oil and two in ten at 100 mm being along the pressboard surface. With an edge radius of 10 mm the breakdown voltages at 50, 100 and 150 mm were 680, 980 and 1 100 kV, the only breakdowns on the tubes being three out of ten at the 100 mm gap.

Effect of Dimensions of Tube.—The flashover voltage does not depend on the diameter or wall thickness of the tube.

Effect of Electrode Shape.—The dimension of the electrode normal to the dielectric surface [*h* in Fig. 5(*a*)] has a large effect, as shown in Fig. 6. The rounding of the edge in contact with the dielectric [P in Fig. 5(*a*)] does not transfer all flashovers from the solid surface to the oil, and the breakdown voltage for a given exposed length of dielectric (exceeding the electrode gap by twice the radius) is less than with sharp-edged electrodes, so that rounding the edge seems to be of doubtful value.

Effect of Voltage Duration.—The effect of impulse duration on the flashover voltage between foil electrodes is large at small spacings, but relatively small at large spacings. This was unexpected, but it is consistent with time lags observed with 1/50 microsec impulses, which were in general larger for small spacings.

Effect of Polarity Reversal.—The effect of any residual charge left by a previous impulse of opposite polarity appears, from the observations at 100, 300 and 650 mm in Fig. 6, to be small.

Effect of Gum Fixing the Outer Layer.—In normal manufacture the outer layer of pressboard tubes is fixed with gum. The two points for foil electrodes at 650 mm spacing in Fig. 6, before and after removal of the outer layers, indicate that the gum had no great effect on the flashover voltage.

(6.2) Flashover under Combined Tangential and Normal Stress

To study the effect on surface flashover of a large component of normal stress, electrodes were mounted on 13 mm-bore 13 mm-wall dielectric tubes with an inserted or built-in axial conductor, as shown in section in Fig. 5(*b*), or on a 13 mm or 6·4 mm-thick dielectric sheet lying on an earthed metal plate as shown in Fig. 5(*c*), one electrode being connected to the metal rod or sheet.

Flashover voltages between electrodes on pressboard tubes or sheets 13 mm thick are given in Fig. 7. Breakdown starts at the electrode not connected to the metal rod or sheet, and references in Fig. 7 to polarity are to the polarity of this isolated electrode. The full lines relate to 1/50 and the dashed lines to 1/5 microsec impulses, and the upper pair to negative polarity. Flashover voltages with 1/50 microsec waves on 6·4 mm sheets of pressboard and three types of resin-bonded paper are shown in Fig. 8.

Effect of Shape of Electrode and Test Sample.—It appears possible to make the very wide generalization that the flashover voltage is the same for tubes and sheets of the same thickness, and does not depend on the dimensions of the isolated electrode. Comparison of Figs. 7 and 8 indicates that doubling the insulation thickness does not appreciably affect the flashover voltage.

Effect of Voltage Duration.—The difference between the flashover voltage with 1/5 and 1/50 microsec waves is large at small spacings but small at large spacings. As in the case of flashover under tangential stress this was unexpected, but it is consistent with time lags observed with 1/50 microsec waves, which were generally about a microsecond at large spacings but of the order of tens of microseconds at small spacings.

Effect of Polarity.—The negative flashover voltage is from 10 to 20 % higher than the positive.

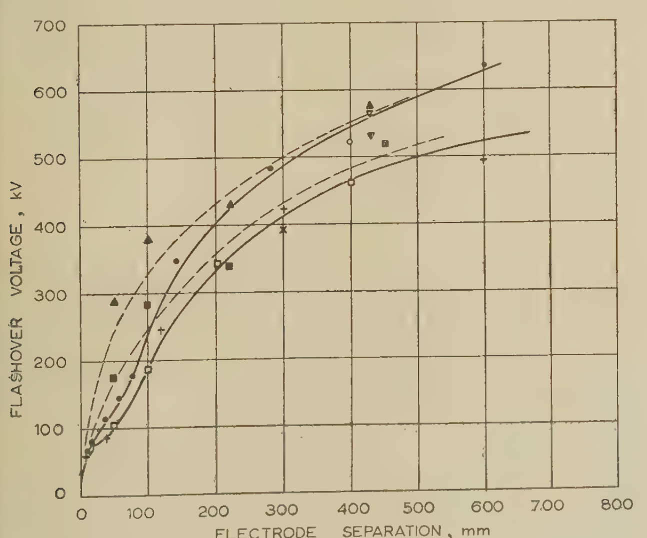


Fig. 7.—Flashover of pressboard tubes and sheets with normal and tangential stress.

□ Sheet, positive, 1/50 microsec wave.
○ Sheet, negative, 1/50 microsec wave.
+ Tube, positive, foil electrodes, 1/50 microsec wave.
× Tube, positive, disc electrodes, 1/50 microsec wave.
● Tube, negative, foil electrodes, 1/50 microsec wave.
▽ Covered rod, negative, foil electrodes, 1/50 microsec wave (5 samples).
▲ Tube, negative, foil electrodes, 1/5 microsec wave (5 samples).
■ Tube, positive, foil electrodes, 1/5 microsec wave.
▼ Covered rod, negative, foil electrodes, 1/5 microsec wave (5 samples).

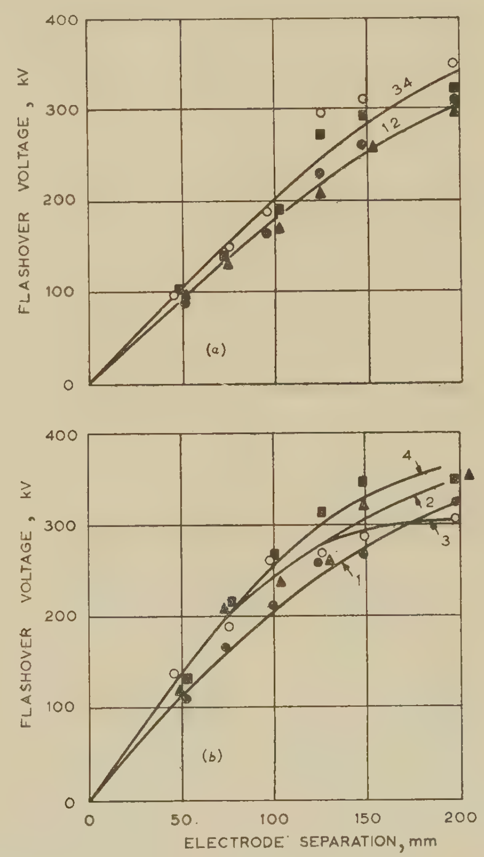


Fig. 8.—Flashover of 6·4 mm sheets in oil, 1/50 microsec waves.

(*a*) Positive.
(*b*) Negative.

1 ● Phenol-formaldehyde-resin-bonded paper.
2 ▲ Aniline-formaldehyde-resin-bonded paper
3 ○ Melamine-formaldehyde surface on 1
4 ■ Oil-impregnated pressboard.

With the geometry considered in this Section, breakdown starts by discharges at the isolated electrode at a voltage which is scarcely affected by the length of the flashover path. The short-time breakdown observed at large spacings indicates a high increase in the rate of propagation of these discharges with increase of applied voltage. The higher the voltage the greater is the amount of ionization to be expected in the discharge, and if breakdown is not completed quickly, the greater will be the amount of positive and negative charge separation and the greater the consequent field modification due to space charge. Such modification will be in a sense to oppose the propagation of the discharge, and it is suggested as a probable explanation why at large flashover distances breakdown is likely to take place quickly or not at all.

(7) COMPARISON BETWEEN SHEETS AND TUBES OF THE SAME MATERIALS

The flashover voltages given in Fig. 7 at a gap of 430 mm were obtained during an attempt to measure puncture voltage. The intention was to compare the puncture voltage of tubes with that for 6·4 mm sheets, where the stress at the pressboard surface for a given voltage should be approximately the same as at the inner surface of the tube, and to determine the effect of an oil film between electrode and dielectric by comparing results on tubes and covered rods. As flashover occurred no evidence was obtained on the effect of an oil film on the puncture voltage, but the voltage reached was appreciably greater than the puncture voltage (425 kV) of 6·4 mm sheets. This is attributed mainly to the greater strength of thin sheets mentioned earlier (the tubes being made from a roll of paper) and partly, perhaps, to a greater time lag for puncture in a divergent field. It appears reasonable to regard oil-impregnated pressboard as the same material, whether in sheet or cylindrical form.

Similar tests on tubes of phenol-formaldehyde-resin-bonded paper containing 50% resin caused puncture at an average value of 320 kV, and covered rods punctured at 350 kV—appreciably less than the 450 kV puncture voltage of 6·4 mm sheets. In tests on tubes without an inner conductor the breakdown path at gaps beyond 100 mm did not often follow the surface but sometimes scored a deep channel; it sometimes followed an interlayer surface, with varying amounts of mechanical damage up to fracture of the tube, and sometimes it punctured the tube and followed the inner surface. The flashover voltages were very variable, with a coefficient of variation of the order of 30%. Tests on tubes with 40% resin content were more consistent, and breakdown was usually along or near the surface. Mean flashover voltages at 200 mm and 1 000 mm were 460 and 1 140 kV—these figures are comparable with those for pressboard (see Fig. 6), as was the consistency of the observations.

It seems that tubes and sheets of resin-bonded paper of the same composition may differ in properties. In forming tubes it is not possible to apply over the whole outer surface the high pressure used in manufacturing sheets. Some 6·4 mm sheets with 50% resin content specially manufactured under reduced pressure punctured at 270 kV, with separation of the layers as occurred in the flashover tests on tubes. This suggests that the difference in applied pressure during manufacture may be the explanation of the different properties of the sheets and tubes containing 50% resin. The effect, as shown, varies with resin content, and probably depends also on the paper used.

(8) APPLICATION OF RESULTS

The puncture-voltage data are of general application where the insulation thickness is small compared with its radius of curvature and where the uncovered electrodes are in contact with the outer layers of solid. Insulation covering the electrodes, such as paper wrapped round the conductors of a transformer winding, would be expected to increase the puncture voltage. While wrapped insulation remains undamaged, however, the winding cannot be effectively converted by discharges into a plane electrode as an uncovered electrode can, and observation suggests that discharges unconnected to an electrode are less extensive. The stress in the oil gaps between the solid layers may therefore be less uniform, so that breakdown in these regions may occur more readily. Thus the increase in puncture voltage due to the conductor covering may be less than that expected.

The data on flashover of tubes under tangential stress apply to electrodes such as terminals and tapping points or switch contacts mounted on tubes or rods of insulation, but only a limited degree of generalization is possible, as shown by the extreme cases (Fig. 6) of foil and disc electrodes.

The data on flashover under combined normal and tangential stresses are of general application (for insulation about 13 mm thick) between the exposed end of a transformer winding and the core, or between two coaxial windings of different length, or between electrodes mounted on metal rods covered with insulation. Further data obtained on thicker insulation in either cylindrical or sheet form as convenient should be of general application.

(9) CONCLUSIONS

With some geometrical arrangements of solid and liquid dielectrics in combination it seems possible to make a degree of generalization about breakdown which may be of help to designers of high-voltage equipment. It would be impracticable to provide data for arrangements of all possible shapes and sizes, but information of the type given in the paper may reduce the work necessary for the development of new designs, either by eliminating the need to consider some variables, by indicating qualitative preferences, or by suggesting more convenient forms of suitable test sample than an actual model of the proposed system. For example, in considering the puncture voltage of the configuration in Fig. 1, the effect of electrode shape can be ignored, and there seems to be an advantage in the use of thin sheets at large gaps, not only in respect of puncture strength with 1/50 microsec waves, but in increased strength against impulses of shorter duration, while in considering flashover in the presence of a large component of stress normal to the surface, the cylindrical and plane configuration of Figs. 5(*b*) and 5(*c*) appear to be interchangeable.

(10) FUTURE WORK

It is proposed that further work should include:

(*a*) Puncture of alternate layers of solid and liquid between covered conductors representing transformer windings.

(*b*) Flashover with a high component of normal stress, using two or more layers of solid insulation.

(*c*) Flashover under tangential stress between conductors passing through a sheet of insulation.

(*d*) Flashover between insulated conductors passing through a sheet of insulation.

(*e*) Flashover along an irregular path such as that formed by alternate washers and packing pieces between end coils and a clamping plate.

(*f*) Some observations at 90° C.

(11) ACKNOWLEDGMENTS

The work was carried out in the Electricity Division of the National Physical Laboratory on behalf of the British Electrical and Allied Industries Research Association. The paper is published by permission of the Director of the Laboratory, and with the approval of the Director of the Association.

DISCUSSION ON THE ABOVE THREE PAPERS BEFORE THE JOINT MEETING OF THE SUPPLY AND MEASUREMENT AND CONTROL SECTIONS, 25TH APRIL, 1956

Mr. R. Davis: The electric strength of the dielectric barrier between conductors at different potentials is not readily calculable from a knowledge of the strengths of the components and the laws of electrostatics except in the case of a geometrical arrangement of conductors producing a uniform field. For the very complex field forms associated with transformers and the somewhat less complex forms involved in cable construction, it is necessary to plan investigations, the results of which should lead to the greatest degree of generalization. This is what Messrs. Standring and Hughes have tried to do for transformers and Messrs. Hall, Kelk and Skipper for cables.

Fig. 3 of the paper by Messrs. Hall and Kelk shows a relation between the strength of single sheets of paper and paper in cable models. In deriving the relation an unspecified correction has been applied to the values for models. Where practicable, I think it is desirable to separate experimental data from the analysis and interpretation of such data. This gives the reader, presented with the data, the opportunity of making independent analysis and generalization.

Messrs. Hall and Kelk show that certain paper characteristics, such as mean thickness, uniformity and apparent density, are functions of the measuring technique. This leads them to distinguish a fine and a coarse structure, and they proceed to show by painstaking experiment that breakdown depends on the fine-structure characteristics rather than the coarse. It is not clear, however, in view of Section 2.2.2 and the statement at the end of the second paragraph of Section 4, to what extent the generalizations are based on fine-structure characteristics.

Messrs. Hall and Skipper show that many factors affect the strength of lapped impregnated paper dielectrics, but it is surprising that no mention is made of the electric strength of the liquid impregnant, especially in view of the conclusion that the impulse failure of a lapped dielectric is initiated at the oil–paper interface. To assess quantitatively the effects of different variables, they make use of statistical methods. For example, in Section 4 of the paper by Messrs. Hall and Kelk, the variability ascribable to impermeability is 19% and that to uniformity 28%, but the variability ascribable to both together is 78·5%. Although these effects are apparently not additive, the residual variation, which I understand to be the unaccounted variation, is derived by a process of subtraction. In problems involving many variables, statistical methods could be very valuable if they led to factors which could be combined in a simple way, e.g. by addition.

Mr. L. C. Richards: The paper by Messrs. Standring and Hughes covers a very big subject with many variables, and a useful start has been made in considering some of these.

I have two criticisms to make. One relates to the use of many different symbols to indicate the curves; it would have been much simpler had each curve been numbered or labelled individually with the appropriate caption. The other relates to the use of millimetres instead of inches in dealing with the thickness of materials tested. As obviously all the material used was supplied to fractions of an inch it would have been much simpler to talk, for instance, of a $\frac{1}{4}$ in sheet than of a sheet 6·4 mm thick.

The use of 20° C as a basic temperature is unfortunate, as insulation in transformers normally operates at higher temperatures than this. Would it not be possible to have certain of the more frequently used materials tested over a range of temperatures varying from 20° C to 90° C?

I do not understand the authors' meaning when they state that the effect of a previous impulse just below the breakdown voltage appears to be negligible. Surely the insulation under impulse test is subject to fatigue, and each application must have some effect. In fact, when one is approaching the breakdown voltage it is very likely that discharge will be taking place and serious fatigue occurring. Did the authors observe and record any such cases?

There is no reference in the paper to power-factor readings, although these are of extreme value when dealing with insulation. Have the authors made any studies of such readings with the idea of trying to relate them to the condition of the insulation in respect of breakdown under impulse conditions?

Mr. C. C. Barnes: Recently increasing attention has been paid to the problem of operating cables at higher stresses and temperatures, and inevitably the margin of safety is being reduced. Therefore expedients which do not matter under less onerous conditions now become of vital importance, and a close scrutiny of cable materials, techniques and processes is essential.

One end-point of the work described is to develop power-cable systems for the highest voltages designed to obviate ionization under all conditions of load, or even overload, experienced in service.

The two methods employed are:

(i) To apply pressure to the impregnant so that any tendency to form gas pockets or voids is prevented.

(ii) To introduce high-pressure gas into the dielectric and thus raise the voltage required to initiate discharge.

Fig. A [overleaf] provides a summary of modern pressure-cable systems.

Tests on materials, cables and their accessories are numerous and varied. In so far as cable systems are concerned, however, they can be subdivided as shown in Table A.

Table A

TESTING OF MATERIALS, CABLES, JOINTS AND TERMINATIONS

Test location	Type of test		Scope of test	
Laboratory	Development tests	on materials	Electrical Mechanical Chemical	Properties, etc.
Laboratory	Type tests	on cable systems	50 c/s a.c. Impulse tests Mechanical tests Sample tests	
Factory	Routine factory tests	on cables, joints and terminations	Electrical Mechanical (Bending tests, etc.)	
Site	Routine tests	on cable systems	Electrical and Hydraulic or Pneumatic	

Fig. B shows an assembly of 3-core 132 kV oil-filled cable joints and terminations ready for a 640 kV impulse withstand test, with the conductor heated to 90° C. It gives an indication of the expensive and complex equipment used for testing super-voltage cables, and also emphasizes the necessity for preliminary investigations of the type described in the papers.

Fig. 3 of the paper by Messrs. Hall and Kelk is difficult to understand. It is not clear which test results are plotted; also a very wide spread of results is indicated, which is worthy of comment. The observations in Section 2.1.2 on the correction of cable-model strengths to correspond to a constant paper thickness ($3\frac{1}{2}$ mils) seems to be a sweeping simplification. Is one correction

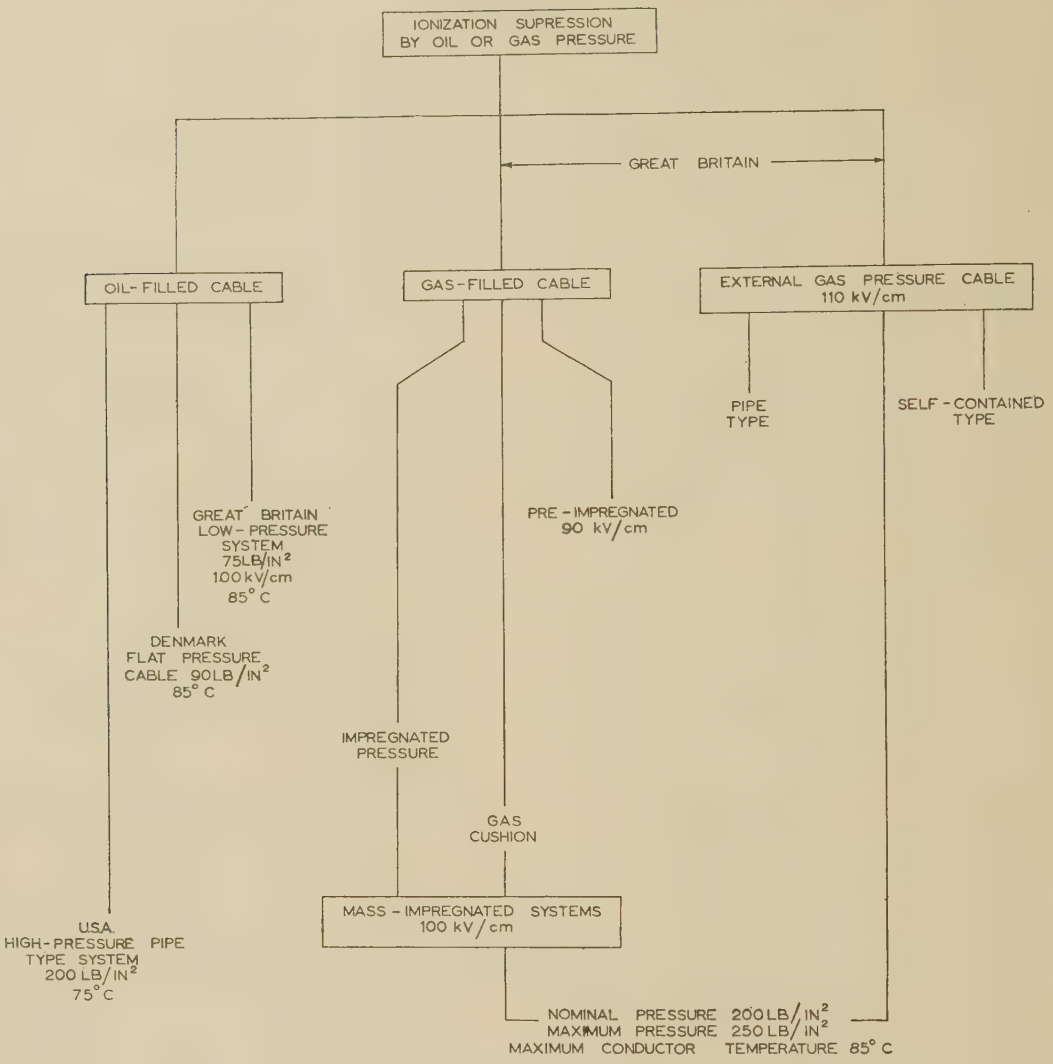


Fig. A.—Super-voltage cable systems.

The design stresses stated are based on successful service experience and/or type tests and refer to a system voltage of 132 kV.

factor really adequate to adjust from cable-model tests to values for a flat paper tape of $3\frac{1}{2}$ mil thickness?

Detailed measurements on small areas of paper are described, and it is concluded that it is better to specify the paper in terms of a high impermeability and a high degree of uniformity. The authors' views on the optimum values and limits of deviation for these properties will be of interest.

With regard to the paper by Messrs. Hall and Skipper, recent impulse tests by cable makers on miniature cable systems have shown generally the advantages of thin paper tapes, an increase in paper density, closely controlled processing techniques, etc.

The test specimens described in Section 2.1 are very small, and a major problem in the manufacture and installation of power cables with a lapped impregnated dielectric is the bending which the cable dielectric must successfully withstand.

Cables manufactured at present for the highest voltages are generally provided with a screen, often of carefully selected carbon-black paper, applied over both the conductor and the dielectric. Have the authors given consideration to this development?

The Ferranti 10 kV cable installed in 1891 used brown paper soaked in ozokerite wax as the insulant, and at present the practice is still similar, but the detailed techniques have pro-

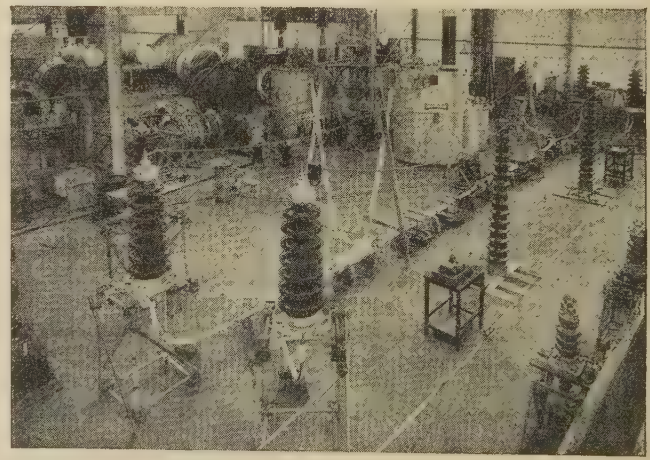
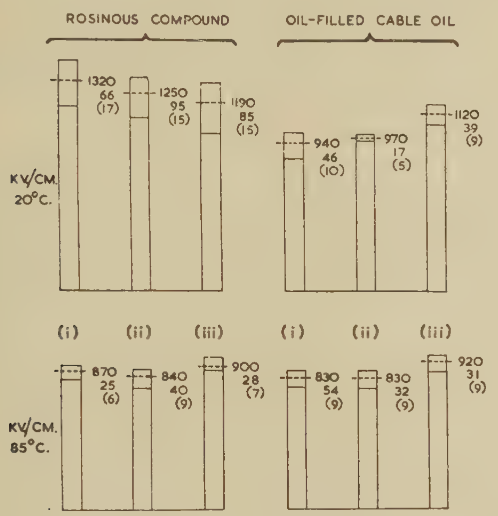


Fig. B.—Test assembly for hot impulse voltage test on 3-core 132 kV oil-filled cable and accessories.

gressed over the subsequent 65 years. I suggest, however, that the numerous types of new synthetic materials now available and the ever-expanding knowledge of the type of chemical structure most resistant to high electric stress means that new materials, new cable structures, and simplified production techniques will result, in due course, in smaller, lighter and more efficient super-voltage cables.

Finally, I must stress that, whilst the authors have shown with great ability certain investigations relating to paper and lapped cable dielectrics, the technique of making super-voltage cables is a highly-skilled practical issue which may be controlled by statistical analyses, but the continuous need for close and rigid supervision during every stage of manufacture must not be overlooked.

Dr. B. Salvage: Fig. C gives the results of measurements we have made of the impulse strength of model cables constructed



Paper	Thickness	Density	Air impermeability
	mils	g/cm³	Emanueli units × 10^6
(i)	5·2	0·58	0·20
(ii)	4·8	0·69	0·41
(iii)	5·8	0·79	1·5

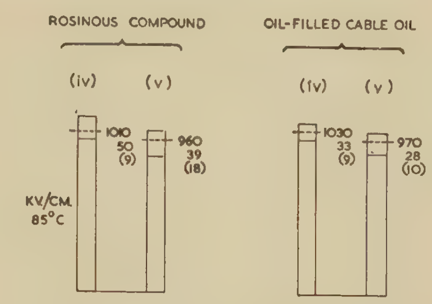
Fig. C.—Effect of paper density and impermeability.

from three wood-pulp papers supplied by the same manufacturer and having approximately the same thickness, but different densities and air impermeabilities. The models have been impregnated with compound consisting of mineral oil with the addition of 16% of refined rosin by weight, and oil-filled cable oil similar to the authors' impregnant C.1. The mean impulse strength in kilovolts per centimetre is stated for each test and the range is indicated; beneath the mean value are given the standard deviation in kilovolts per centimetre and the number of individual measurements on which the mean is based.

To separate the effects of paper density and impermeability we have obtained a series of wood-pulp papers from the same manufacturer having practically the same characteristics, with the exception of the particular one under investigation (Figs. D and E).

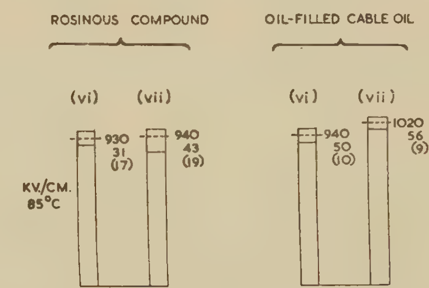
Fig. F gives results obtained with a paper having low density and high impermeability compared with one having more normal characteristics.

Our conclusions, therefore, which are in agreement with those



Paper	Thickness	Density	Air impermeability
	mils	g/cm³	Emanueli units × 10^6
(iv)	5·6	0·67	1·4
(v)	5·4	0·80	1·4

Fig. D.—Effect of paper density.



Paper	Thickness	Density	Air impermeability
	mils	g/cm³	Emanueli units × 10^6
(vi)	4·7	0·89	1·5
(vii)	4·6	0·88	30

Fig. E.—Effect of paper impermeability.

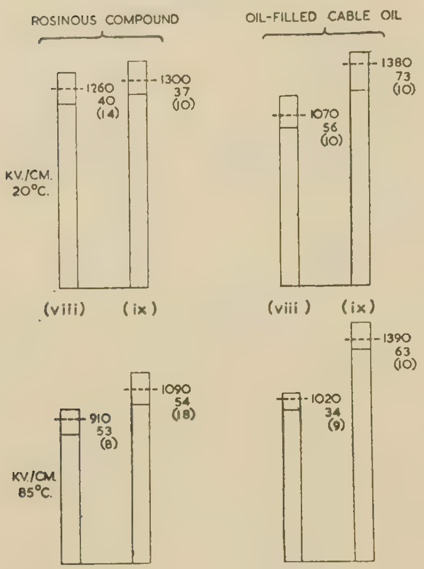
of Gazzana-Priaroggia and Palandri,* are that an increase in the density of the paper causes a decrease in the impulse strength of the dielectric, consistent with the increased permittivity and hence higher butt-gap stresses; an increase in the impermeability has no significant effect with viscous impregnants but results in a considerable improvement in impulse strength with impregnants having low viscosity. When a paper having a high density and high impermeability is impregnated with an oil or compound of low viscosity, the effect of the impermeability generally predominates over that of the density.

Our deductions concerning the effects of paper density have not been influenced by the surface uniformity of the papers we have used; for example, papers (i), (ii), (iii), (iv) and (v) have surface roughnesses of 610, 790, 91, 220 and 230 as measured in units of cubic centimetres of air per minute for a pressure difference of 1·5 in of water, using an apparatus of the Bendtsen type.†

My paper, to which Messrs. Hall and Skipper refer in Reference 6, dealt solely with the impulse strength of solid-type and gas-cushion cables at ambient temperature. Our recent

* Gazzana-Priaroggia, P., and Palandri, G.: 'Research on the Electric Breakdown of Fully Impregnated Paper Insulation for High-Voltage Cables', *Power Apparatus and Systems*, 1956, No. 22, p. 1343.

† Sankey, C. A., and White, P. H.: 'Standardisation of the Bendtsen Tester for Measurement of Newsprint Paper Roughness', *Pulp and Paper Magazine of Canada*, 1948, 49, p. 99.



Paper	Thickness	Density	Air impermeability
	mils	g/cm³	Emanueli units × 10^6
(viii)	3·2	0·82	1·3
(ix)	3·0	0·76	60

Fig. F.—Effect of low density and high impermeability.

experiments support the conclusion stated therein that the cable impulse strength under these conditions is directly related to the impulse strength of the compound in the butt gaps in the region of maximum stress. However, in oil-filled cables and in solid-type and gas-cushion cables at elevated temperatures, phenomena initiating breakdown are not confined solely to the butt gaps; in particular the 'barrier effect' of the paper fibres is important in hindering ionic movement and increasing the impulse strength of the dielectric.

Mr. H. F. Church: In Fig. 4 of the paper by Messrs. Hall and Kelk impulse strength of single sheets is independent of thickness, whereas in the paper by Messrs. Hall and Skipper the strength of cable models is strongly dependent on thickness. The difference suggests imperfect impregnation or edge effects with the cable models.

In view of the use of pre-impregnated cable paper which may contain moisture, can the authors state whether the presence of moisture is likely to affect their conclusions, which are based on work on dry samples?

In the paper by Messrs. Hall and Kelk there is no mention of conducting inclusions, which are of great importance in capacitor papers. Could not the presence of local concentrations of small conducting carbon particles explain part of the residual unascribed variations in the impulse strength of cable paper?

The local geometry of impregnated-paper dielectrics affects not only impulse strength but also the long-term failure rate at working stress. With impregnated paper capacitors, life values usually cover a considerable range; e.g. with a few hundred similar capacitors a range from 1 to 100 is usual. This is far higher than that found with any other property, but it can be explained in terms of variation of the shortest path through the cellulose, as determined by local thickness variations or the presence of conducting inclusions. Since the life varies inversely as about the fifth power of the operating stress, the fifth root of life should vary in the same way as the shortest path. If, in fact, the frequency distribution of the fifth root of life is plotted, a relationship is obtained which is exactly like the type of distribution observed for impulse strength, i.e. an approximately normal distribution with reasonable standard deviation (10–15%). The unexpectedly wide variation of the life values is thus explained.

Mr. D. H. Booth: The paper by Messrs. Hall and Skipper illustrates very well the general advantages to be gained by this form of model-testing technique. In particular, the very large number of tests that can be carried out using this method contrast vividly with full-size cable testing. For example, the authors mention that 1 500 model tests were used in arriving at their conclusions. This, of course, will result in a considerable saving in research expenditure and allows the consideration of a very large number of constructional and material variables without the inherent inconvenience of full-scale manufacture.

In spite of these advantages the whole conception may be of little value unless results obtained on models relate directly to the finished cable. The authors consider their cable dielectric to be 'representative of that in full-size cables'. It is on this opinion that the main value of their work lies, and it is unfortunate that they did not feel disposed to elaborate this theme, and so one can only compare their results with data already published on full-size cable.

The stress level of breakdown results, the lack of a stranding effect, the polarity reversal effect and the effect of decrease in strength with conductor size are all factors in which the data in the paper are in opposition to those given in recent papers on the performance of full-size high-voltage cables. I would therefore appreciate the authors' comments on these discrepancies.

In the paper by Messrs. Hall and Skipper the authors note that the increase of impulse strength at atmospheric temperature with paper density is more significant with the less viscous type of impregnant. With tests carried out on the gas-filled form of dielectric, where an extremely viscous impregnant at atmospheric temperature is used, we have found no effect of paper density, whereas the effect of impermeability agrees well with the figures quoted in the paper. It therefore appears that there is little advantage in increasing the Gurley density above 1 000 sec/100 cm³, and I would go even further and state it is possible that, with increased impermeability, one can produce such a poor paper uniformity by the use of long beating times that the impulse strength is decreased.

I would be interested in any data that the authors may have on the effect of moisture content on impulse strength. With reference to the gas-filled dielectric we have found no change in impulse strength with moisture contents below 0·8%.

Only a few years ago there appeared to be strong opposition to the use of even the most simple statistical methods, and I feel that the authors have well illustrated the advantages to be gained from correct statistical design of experimental work. Secondly, it is of great importance that we now have two further papers showing that the cable industry is taking a more direct lead in deciding exactly what materials it requires, and that it is developing methods for accurately assessing the desired properties. In particular, the concentration on breakdown strength instead of dielectric loss is to be commended.

Dr. G. Palandri (*Italy*): I wish to make a few comments and to compare the results obtained by the authors with those obtained by the organization with which I am associated, and which have recently been published.*

In Section 3.3.1 of the paper by Messrs. Hall and Skipper, it is shown that the variation of impulse strength with temperature is related to the viscosity/temperature characteristic of the impregnant. We are in complete agreement with these findings, and

* GAZZANA-PRIAROGGIA, P., and PALANDRI, G.: 'Research on the Electric Breakdown of Fully Impregnated Paper Insulation for High-Voltage Cables', *Power Apparatus and Systems*, 1956, No. 22, p. 1343.

I am glad that we have, quite independently, come to the same conclusion on this much debated point.

In Section 3.3.2 it is stated that the impulse strength of fully-impregnated paper dielectric is independent of pressure. It is unfortunate that the tests described by the authors are limited only to type C.4 impregnant and to ambient temperature. With type C.1 impregnant we have found a very significant increase in impulse strength due to applied pressure on fully impregnated dielectrics. We have also found that, with an impregnant of the C.4 type, the effect of pressure is evident when tests are carried out at 85°C. In the latter case the lowering of the impulse strength due to change of viscosity of the impregnant was partially compensated by the effect of pressure. It may be of interest to add that the effect on fully-impregnated dielectric is quite independent of how the pressure is applied, namely by nitrogen or oil pressure.

With regard to the effect of repeated stressing discussed in Section 3.4.2, we have found no decrease in breakdown strength in the case of dielectric fully impregnated with the C.1 type of impregnant even after the application of 1 000 impulses. The authors find a decrease of the order of 13%, and I wonder whether this may be due to imperfect impregnation.

With regard to Section 3.4.3, qualitatively we are in agreement with the authors, but our observations, at least with an impregnant of the C.1 type, show that the reduction of impulse strength due to polarity reversal is not greater than 5%. Again I wonder whether the discrepancy between our results may be due to imperfect impregnation.

With regard to Section 3.5.3, our tests on cable models impregnated with oil of the C.1 type show no significant difference in the electric strength of stranded conductors in the range 1–1·5 in, and insulation thicknesses ranging from 1·5 to 3·5 mm.

The results shown in Table 13 indicate no significant difference between the impulse strengths of stranded and smooth conductors. We have found, however, a significant reduction of impulse strength (about 10–15%) on cable models with a conductor diameter of 1·1 in impregnated with a C.1 type impregnant when passing from a smooth to a stranded conductor.

In the paper by Messrs. Hall and Kelk, I feel that it would have been useful had the authors given sufficient experimental data to correlate mean values and dispersion of impulse strength to thickness histograms or transparency records taken on paper.

Our results show that the linear correlation between breakdown strength and thickness shown in Fig. 4 is valid only in the case of multi-ply paper; with single-ply paper the electric strength diminishes as the thickness increases.

Mr. A. E. Brierley: The paper by Messrs. Standring and Hughes gives some very useful information as applied to transformer design and also to some extent to the testing of transformers.

The reduced strengths found when applying impulses of alternate polarities add further support for the necessity of including chopped waves in tests on transformers.

With reference to the deterioration in strength when applying repeated impulses, I have found that the marks left on the dielectric surface by discharging prior to breakdown tend to fade with time. These marks may be partly due to the forcing of gas into the surface of the dielectric by the discharge. It would be interesting to know whether the reduced strength is a permanent effect or whether there is a recovery of strength with time. Would the authors consider this deterioration to be of any importance when considering the relative merits of impulse testing as a type test or a routine test?

Fig. G shows the results of impulse breakdown tests between paper-insulated conductors with various oil spacings between the conductors. It can be seen that, where the solid insulation

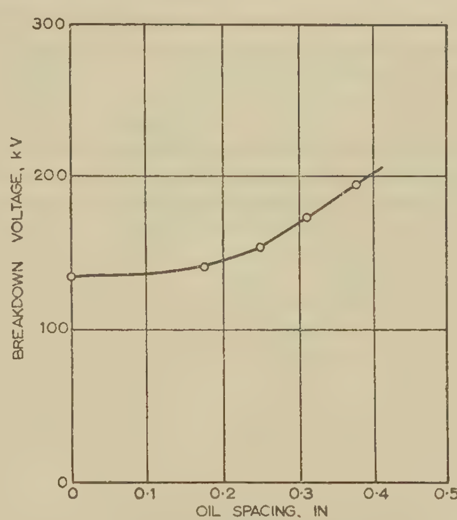


Fig. G.—Breakdown between paper-insulated conductors: 0·040 in paper + oil + 0·040 in paper.

occupies more than 25% of the total spacing, the variation in oil spacing has little effect on the strength. This is due to the oil breaking down at a voltage well below that required to puncture the solid insulation.

I would expect some of the curves in Figs. 2 and 3 to have a similar flat portion for the lower spacings. Perhaps some of the points could be interpreted in that direction, especially the results for 6·4 mm-thick pressboard sheets.

As the proportion of oil to solid insulation is increased, the range will finally be reached where the effective strength of the whole assembly is that of the series oil gaps. When breakdown of the oil occurs, puncture of the solid insulation will rapidly follow.

Mr. F. C. Walmsley: In Section 6.2 of the paper by Messrs. Standring and Hughes, there is an implication that the thickness of tubes—or sheets—has no appreciable effect on the flashover value. This is rather contrary to what has been more generally accepted from earlier work by German workers and by Goodlet. It had been shown that the surface breakdown was proportional to the thickness and inversely proportional to the square of the distance, along the surfaces between the electrodes.

In Section 7 the authors deal with the comparison between sheets and tubes of the same materials and have found inconsistencies, particularly in relation to synthetic resin-bonded paper materials. They have very correctly indicated some of the factors which contribute to the differences, but, as already shown, the paper structure plays an important part. In addition, whereas with the cable compound the maximum measure of impregnation can be achieved, with these materials the mixture between the resin and the paper is restricted for a variety of reasons, e.g. mechanical or physical factors. Added to these limitations the consolidating pressure is important, and with some tubular materials this is definitely restricted to a low value.

On the nature of the breakdown of the surface or occurrence of puncture, can the authors state whether it is possible that, at the time approaching breakdown, the permittivity affects the stress distribution, when it is borne in mind that, for oil-impregnated pressboard, it is approximately 3, with a 40% resin content about 4, and with 50% resin content s.r.b.p. it is of the order of 5?

Dr. F. J. Miranda: The papers by Messrs. Hall and Kelk and Hall and Skipper go a long way to supplying much-needed information to cable designers. However, it is important to stress the limitation of cable models. Flexibility, for instance,

is ignored, and whilst lapping tensions are a major consideration in the design and manufacture of a cable, the authors have shown that this is a factor of no importance in cable models.

Another limitation is that the papers cover mainly fully-impregnated paper dielectric, whilst only certain types of cable are fully impregnated. The practical importance of this can be seen from the results given in Table 6 of the paper by Messrs. Hall and Skipper, which show the effect of gas pressure on a drained dielectric. An extension of this investigation to cover test temperatures up to, say, 85° C would have given useful information to the cable makers.

With regard to fatigue effects, the 13% drop in breakdown strength observed by the authors is not confirmed by our experience on fully impregnated dielectrics, which is based on a large number of tests on both cables and cable models. Our results show no fatigue even with hundreds of impulses.

We associate fatigue with discharges caused by sharp-edged electrodes or, within the volume of dielectric, owing to the presence of gas. For this reason we rather suspect that edge effects are not entirely eliminated in the authors' electrode system, or, alternatively, that the insulation was not fully impregnated when tested.

The authors' technique of transferring the impregnated samples to an open oil test bath is open to criticism. Partial draining during the transfer appears possible, and it would, of course, be more serious the lower the viscosity of the impregnant. If this explanation of the observed fatigue be correct, a number of comparisons made with different impregnants will not necessarily give a true picture of relative merits.

The observation in Section 3.3.2 of the paper by Messrs. Hall and Skipper, that application of pressure to the impregnant in a fully-impregnated dielectric causes an increase in breakdown strength with 200 impulses at each voltage level, lends support to the partial drainage theory. In discussing the results the authors give a different explanation. However, another element in support of partial drainage is the scatter of results, stated by the authors to be very large. An analysis of the results recently published by Gazzana-Priaroggia and Palandri* shows that, in their tests, the scatter was fairly small. Their equipment, however, allowed them to test samples in the same vessel in which impregnation had been carried out.

The observation made in Section 3.5.1 of the same paper, that electrode material affects the scatter of results, is interesting. As it seems very unlikely that the work function of the material can play any part at the test gradients, can the authors suggest an explanation other than surface smoothness?

Dr. P. R. Howard: Fig. H shows the breakdown strength of lapped paper dielectric as a function of the number of butt gaps in the breakdown path; the curve given in Fig. 3 of the paper by Messrs. Hall and Skipper, together with the results obtained during similar work at the N.P.L. with papers of lower densities and impermeabilities, are plotted. The difference in breakdown stresses between the two sets of results can be entirely accounted for by differences in paper thickness, densities and impermeabilities; the impregnant in all cases was the same. It appears from Fig. H that the effect of an increase in the number of butt gaps overrides any advantage derived from the use of high-quality paper. Although cables are not manufactured with a 50/50 registration, there are a considerable number of oil gaps in the radial path, and it is therefore doubtful whether there would be any advantage in using anything but the most ordinary paper for cable manufacture.

We have also compared the breakdown stress of samples, with the same dimensions, formed on stranded and smooth conductors. Rolled sheet and lapped papers have been applied to various sizes of conductor ($\frac{3}{8}$–$1\frac{3}{8}$ in diameter), and in all cases there was no significant reduction in strength with the stranded conductor. There is, however, indisputable experimental evidence in the case of gas-pressure cables of a stranding effect, and we have attempted to resolve this discrepancy between factory- and laboratory-made cables. This* has led to further work with a homogeneous dielectric consisting of oxygen-free nitrogen. At atmospheric pressure there is no effect due to stranding, but as the gas pressure is increased, there is a gradually increasing difference between the breakdown voltages with smooth and stranded conductors.

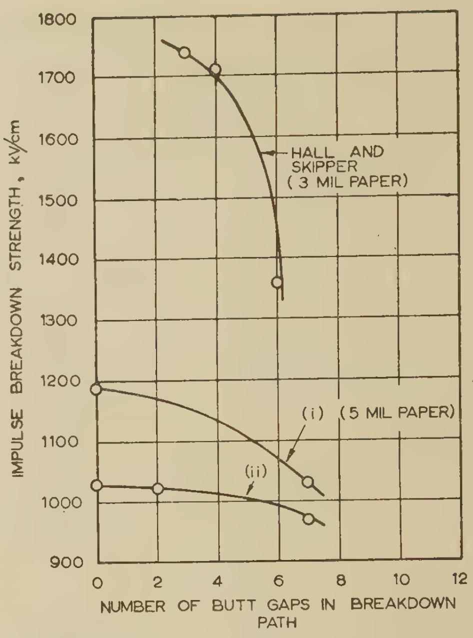


Fig. H.—The effect of butt gaps on the impulse breakdown strength of lapped paper dielectric.

(i) Density = 0·84g/cm³; impermeability = 47 Emanueli units.
(ii) Density = 0·74g/cm³; impermeability = 17 Emanueli units.

Dr. H. House: Some time ago I had to determine the impulse electric strength of impregnated sheets of linen material. The electrodes used were those described in B.S. 1137. In this electrode system the sheet material was placed between the end of a $1\frac{1}{2}$ in-diameter cylindrical upper electrode and a lower electrode which was a 3 in-diameter flat plate. The edges of the upper electrode had a radius of $\frac{1}{32}$ in. When the material was subjected to a $\frac{1}{60}$ microsec impulse wave, streamers extended from the upper electrode along the top surface of the sheet, and a very large number of tests all gave the punctures at the ends of these Lichtenberg streamers, with no breakdowns under the electrodes.

An attempt was made to reduce the voltage gradient E_t along the surface of the sheet by providing a more gradual electrode edge shape, and a calculation, based on a square-law electrode edge curve, was made. The calculation determined the initial response to a step impulse. Since, for the cylindrical symmetry of the electrodes, the mathematics was tedious, a simple estimate of the stress was obtained for two-dimensional electrodes with a similar edge. The form of the tangential component E_t of the surface electric stress, for this case, is indicated in Fig. I(ii). The maximum value of E_t is proportional to $\sqrt{(a\epsilon_2/\epsilon_1 d)}$, and this can be reduced by using an immersion medium of high dielectric constant, ϵ_1, or by using a small value of a, i.e. a more gradual

* Gazzana-Priaroggia, P., and Palandri, G.: 'Research on the Electric Breakdown of Fully Impregnated Paper Insulation for High-Voltage Cables', *Power Apparatus and Systems*, 1956, No. 22, p. 1343.

* Howard, P. R., and Browning, D. N.: 'Stranding Effect in Cables', *Journal I.E.E.*, 1955, 1 (New Series), p. 653.

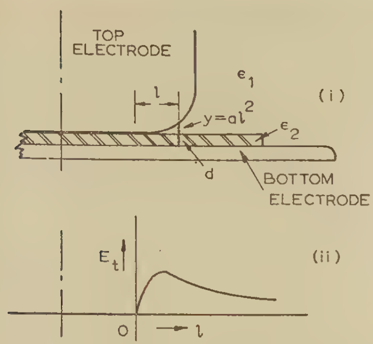


Fig. I.—Electrode system and tangential surface stress.

edge curve. The maximum value of E_t occurs at $l = \sqrt{(\epsilon_1 d/3a\epsilon_2)}$. The reduction of the stress in such electrode systems by the use of high-permittivity immersion liquids is well known,* but simple calculations of this type may allow a ready estimate of the discharge inception voltage for many types of metal-dielectric junctions to be made, and suggest the means of prevention or reduction of these discharges by using suitable fillets of dielectric material or by modifying the electrode shape.

In the cited case of the sheet-material tests, it was permissible to use water as an immersion medium ($\epsilon_{1r} = 80$), and the subsequent tests gave all the breakdowns between the electrodes.

Mr. G. W. Bowdler: The electric strength of a combination of solid and liquid materials is primarily dependent on the product of the electric strength and the permittivity of the liquid, since this is the component in which breakdown usually begins.

In the experiments conducted by Messrs. Standring and Hughes the solid and liquid materials are segregated, and evidence of the initial breakdown of the liquid is quite clear.

On the other hand, in the uniform, or near uniform, field conditions under which Messrs. Hall, Kelk and Skipper have been working the media are not so segregated. The porous solid is permeated throughout by the liquid, but nevertheless in such a combination we would still expect the electric strength to be dependent on that of the liquid. It would be of interest, therefore, as Mr. Davis said in his opening remarks, if we could have some information on the strength of the impregnating compounds which were used.

In tests carried out on paper sheets and wrappings impregnated with transformer oil, the impulse electric strength was related to the impermeability of the paper in very much the same way as is shown in Fig. 5 of the paper by Messrs. Hall and Kelk. It appears that the superior electric strength of oil-impregnated paper over oil alone is due to the obstruction which the network of paper fibres offers to the movement of the ions or solid particles in the oil which may lead to breakdown. Thus, by using paper, we are able to obtain something approaching the intrinsic electric strength of the impregnating media without recourse to an elaborate and expensive drying and filtration treatment.

The papers by Mr. Hall and his colleagues show clearly how the paper must be arranged to get the best results. When this has been done, we must look to the liquid medium for any further improvement in the electric strength of this type of dielectric, and that is one good reason why work on liquid dielectrics should be continued.

* WHITEHEAD, S.: 'Dielectric Breakdowns of Solids' (Oxford University Press, 1951).

Dr. J. H. Mason: It is interesting to consider why the impulse electric strength of oil-impregnated pressboard or s.r.b.p. sheet is nearly independent of electrode shape, whereas the short-time 50 c/s electric strength is considerably lower with asymmetric than with symmetric electrodes.

I think that surface-charge effects may provide the explanation. In most of their tests Messrs. Standring and Hughes applied successive pulses of increasing voltage of the same polarity. The charge remaining on the surface after discharges in earlier tests limits the magnitude of discharges in subsequent higher-voltage pulses, as mentioned in Section 5.3. Consequently differences in discharge behaviour arising from the shape of the electrodes will be minimized in the later high-voltage tests, and the impulse strength will also show little variation with electrode shape. If failure occurred on the application of a single voltage pulse this space-charge effect would be avoided, as shown in Section 3.4.4 of the paper by Messrs. Hall and Skipper, and the impulse strength would probably vary with electrode configuration.

Surface-charge effects would, if anything, enhance the effect of electrode shape if the pulse polarity were reversed in successive tests, or with a.c. electric-strength tests.

Electrode shape has a considerable effect on the impulse strength of Askerel impregnated pressboard,* possibly because surface charge leaks away between successive tests due to the higher conductivity of Askerel compared with oil.

Could the authors give the relative permittivities of the pressboard and synthetic-resin-bonded paper specimens and of the oil and spacers, the time interval between successive impulses and also state whether breakdown over the spacers occurred at the edge of the spacer between the electrodes or somewhere outside the periphery of the electrodes?

Mr. A. R. W. Symons (*communicated*): A feature of the measurements of Messrs. Hall and Skipper is the much higher impulse strength which they find at ambient temperature for lapped paper dielectric impregnated with compound containing polyisobutylene than for dielectric impregnated with oil-filled cable oil. One might be led from Figs. 1 and 2 to conclude that the impulse strength of the impregnated pressure cable at ambient temperature is 40% higher than that of the oil-filled cable. Bearing in mind the present operating stresses of these two types of cable, the question arises as to whether the authors' measurements on models accurately represent the relative impulse strengths of the two cables.

The authors have used a 50/50 registration, which is never employed in actual cables, and they have demonstrated in Fig. 3 that the impulse strength of dielectric impregnated with oil-filled cable oil is considerably increased when a 65/35 or 75/25 registration is used. Experiments we have made with model cables show that the impulse strength of dielectric impregnated with a compound consisting of mineral oil with the addition of 30% of polyisobutylene by weight is much less dependent on the percentage registration than that of dielectric impregnated with oil-filled cable oil similar to the authors' impregnant C.1.

It would appear, therefore, that if a 65/35 or 75/25 registration had been used by the authors, the difference between the impulse strengths at ambient temperature of the dielectrics impregnated with compound containing polyisobutylene and oil-filled cable oil would have been smaller, and that this would have reflected more accurately the relative impulse strengths of the impregnated-pressure and the oil-filled cables.

* DAKIN, T. W., and WORKS, C. N.: 'Impulse Strength Characteristics of Liquid Impregnated Pressboard', *Transactions of the American I.E.E.*, 1952, 71, Part I, p. 321.
SOMMERMAN, G. M. L., BUTE, C. J., and LARSON, E. L. C.: 'Impulse Ionization and Breakdown in Liquid Dielectrics', *ibid.*, Paper 54-69.

[The authors' replies to the above discussion will be found overleaf.]

THE AUTHORS' REPLIES TO THE ABOVE DISCUSSION

Messrs. H. C. Hall, E. Kelk and **D. J. Skipper** (*in reply*): Mr. Davis asks to what extent our generalizations are based on fine-structure characteristics. We have endeavoured to show the importance of these by demonstrating the dependence of impulse strength upon surface uniformity measured with a very small stylus, which is just one assessment of fine structure.

In reply to another point raised by Mr. Davis, as well as by Mr. Bowdler and Dr. Salvage, we have not found a simple relationship between the strength of a lapped oil-paper dielectric and the strength of the impregnant, measured in a test cell.

The somewhat wide dispersion in Fig. 3, referred to by Mr. Barnes, is partly accounted for by the fact that it is not, we agree, completely justifiable to use one correction factor for paper thickness. But our purpose was to demonstrate a correlation sufficiently good to show the relevance of single-sheet tests to tests on lapped dielectrics. The effect upon impulse strength of carbon-black paper, as a screen, has been found to be insignificant.

We find it difficult to deal with the data quoted by Dr. Salvage, as the registration he uses is not given; but it would seem that this is other than 50/50. We suggest that consistent conclusions cannot be drawn from his Fig. C, because the papers differ appreciably in thickness as well as in density and impermeability.

We consider that increase of density, while increasing the stress upon the oil in the butt-gap, is generally accompanied by an increase in the barrier action of the paper and that this latter effect predominates. Fig. D, upon which Dr. Salvage bases his opposite conclusion, refers to tests on only two papers, not differing greatly in density. In stating that his conclusion agrees with that of Gazzana-Priaroggia and Palandri, we think that Dr. Salvage has overlooked their important qualification that the two opposing effects of density cannot be isolated; in fact, Priaroggia and Paladri arrive at a conclusion, based on a wide range of paper densities, substantially the same as ours. Fig. F supports our conclusions on the effect of impermeability; but we would suggest that the inclusion by Dr. Salvage of a paper of better uniformity (and hence, probably, of higher density) would have yielded an even higher value of impulse strength.

In reply to Mr. Church, we have no evidence that conducting particles affect impulse strength, with the thicker papers used in cables. The impulse strength of impregnated paper is unaffected by a moisture content of up to 0·5%. We cannot agree with the suggestion that the dependence of the impulse strength of cable models upon paper thickness is due to imperfect impregnation or edge effects. This dependence was shown in Section 3.2.2 of the paper by Hall and Skipper to be ascribable to variation in butt-gap depth.

Reconciliation of levels of impulse strength between models and full-size cables referred to by Mr. Booth is possible, we think, if proper allowances are made for a number of factors; for example, registration, area or volume tested, conductor diameter, and differences in test procedure. We are not unduly surprised to find that several of our conclusions are at variance with the findings of some papers dealing with tests on full-size cables, as the conclusions of many of these are by no means in agreement with each other. We confirm that the use of extremely short-fibred stock, produced by heavy beating, while increasing paper impermeability, may in the limit lead to a decrease in impulse strength, because of the risk of serious loss of uniformity.

Our more recent work on the effect of pressure with impregnants of different viscosities is in complete agreement with that quoted by Dr. Palandri. We are satisfied that, in our own case, the decrease of impulse strength with a large number of impulses is not due to imperfect impregnation; since, with single shots, and moreover with a high-viscosity impregnant, the strength is found to be independent of pressure. We note with interest Dr. Palandri's comments on the effects of conductor diameter and stranding, but are unable to explain the divergence between our conclusions.

Dr. Miranda's suggestion of imperfect impregnation is covered by our reply to Dr. Palandri. Regarding possible edge effects, we found no evidence of an increase in the proportion of edge failures with an increase in the number of impulses. Before adopting the procedure of rapid transfer to open bath for testing, we took the precaution of comparing tests carried out in this way with tests made in the original impregnation vessel, and found no effect either on the level or dispersion of the results.

So far from indicating, as Dr. Howard suggests, that there is no advantage in using high-quality paper, Fig. H illustrates the advantage of high values of density and impermeability. We are pleased to have Dr. Howard's confirmation of our conclusions on the effect of stranding, which we refer to Dr. Palandri and Mr. Booth, and are interested in his results showing the interaction of this effect with gas pressure.

We agree with the observation of Mr. Symons that the impulse-strength levels given in Figs. 1 and 2 cannot be taken as indicative of the relative levels obtainable in pressure cables and oil-filled cables; there is, we agree, a large interaction between compound viscosity and registration, as Mr. Symons himself finds, which needs to be considered when comparing cold impulse strengths.

Messrs. W. G. Standring and **R. C. Hughes** (*in reply*): We agree with Mr. Richards that our diagrams are open to criticism, and regret that we did not find a more successful form of presentation. Additional labelling of the curves might have made the Figures (Fig. 2 in particular) appear even more difficult to read. In presenting data on a complicated and little understood subject we thought it necessary to give as many experimental results as possible so that a reader who contemplated making use of our information could judge for himself the reliability and range of application of our conclusions and generalizations. A multiplicity of symbols was unavoidable for this purpose, but we tried to draft the text so that the general reader would be able to follow without difficulty any references to Figures without bothering to look at individual points. We consider that for general publication lengths should always be expressed in metric units, which are universally understood; but in this case it would have been better to give both millimetres and inches. The question of temperature is mentioned at the end of Section 1, and in Section 10(*f*). We estimate that the rate of progress would be reduced by a factor of about four if all the work were done at 90° C. The fatigue due to discharges is cumulative and is greater when the polarity is reversed at each impulse, but the 'single shot' puncture voltage is not significantly less than that obtained without reversal. The magnitude of the effect with repeated impulses confirms the conclusion that the effect of one impulse is small in comparison with the 10% to which we consider our figures significant. All our observations were made on material in good condition, so that power-factor measurements would have yielded no additional information.

Some of the marks left by surface discharges appeared to fade with time as described by Mr. Brierley, but most of them involved mechanical damage to the surface layer. We imagine that in operational use in a power system such insulation would be susceptible to deterioration owing to accumulation of impurities along the discharge tracks, and we consider that impulse tests involving discharges are highly unsuitable for routine tests on equipment.

We doubt whether the earlier work referred to by Mr. Walmsley justifies such a positive statement on flashover voltage. The fact

that we found no great effect on doubling the thickness does not imply that there is no effect. In changing from a tube 13 mm thick (Fig. 7) to infinite thickness we should expect to reach the condition of Fig. 6, in which flashover voltage is dependent on electrode dimensions but at a minimum is roughly twice that in Fig. 7. Stress distribution must be affected by permittivity, but from Fig. 8 it appears that flashover voltage is not greatly affected. It may be that with solid insulation of higher permittivity discharges start at a lower voltage in the oil but the discharges relieve the stress so that the effect of permittivity of the solid is reduced. The pressboard observations shown in Fig. 8 are among the highest.

Dr. House refers to calculation of stress at an electrode edge in order to estimate the discharge inception voltage. We doubt whether it is economic (or practicable at the highest voltages) to design equipment which will be discharge free under impulse tests, so that impulse breakdown voltage may bear little relation to discharge inception voltage.

We attribute the dependence, mentioned by Dr. Mason, of puncture voltage at 50 c/s on electrode shape to decomposition of the oil by discharges leading to increasing energy dissipation. The puncture voltage obtained with a sharp-edged electrode at 54 mm electrode separation was not affected by a previous impulse of opposite polarity, which appears to contradict the suggested explanation of the difference with impulses. The time interval between impulses was usually between 15 and 30 sec. Breakdown over the spacer was sometimes inside, but more often outside, the electrodes. The reference to Askarel reminds us that generalizations about pressboard and transformer oil must not be applied to all solids and liquids. The unfavourable properties of Askarel appear to be associated with its use as an impregnant, not as an immersion medium.

DISCUSSION ON 'A HIGH-POWER MECHANICAL CONTACT RECTIFIER'*

MERSEY AND NORTH WALES CENTRE, AT CHESTER, 6TH FEBRUARY, 1956

Mr. D. B. Corbyn: The authors seem to dismiss the double-contact rectifier too lightly, and I believe that the simplicity claimed for the single contact is illusory. A 1955 paper claims 6 min per month average shut-down time during the second year of a 400-volt 80 kA double-contact installation. Double-contact rectifiers usually have two contacts per phase in series, one closing and the other opening the circuit. Wedges give adjustment, but not control. Four manufacturers still use single contacts, one one using double contacts discontinued all single-contact designs after the war. An excited synchronous motor is used for each contact set, the closing instant being varied temporarily by d.c. field control and the opening instant by a.c. phase variation. The speeds of response to frequency and load-angle changes are not critical. Overlap control is effected by a hydraulic regulator continuously operating a rotary phase-shifter, which seems preferable to step control by reversing motor, change-over contactors and relays. What is the function of the authors' polarity generator?

The ultimate design choice depends on reliability. With two contacts, material transfers mainly at closing and does not increase the backfire risk on opening contacts, since backfires usually involve only two or three opening contacts. A contact life of up to one year is claimed.

A sudden fall of supply voltage to 70% normal is handled without backfire, and there is special protection against complete failure. Comparable figures for the authors' design would be interesting.

Switching-in is very simple: resistors and contact-lowering gear are not required, but a very small auxiliary transformer is necessary.

In their experiments on the 6-phase single-way circuit, did the authors experience bad load-sharing between the two halves? This is likely in the circuit shown with any rectifier using magnetic control. Did this possibility influence their choice of the bridge circuit for 270 volts?

Mr. D. R. Smith: The necessity for a 'stiff' driving motor arises from the occurrence of sudden phase changes in the a.c. supply when loads are switched in parallel with the rectifier. A small load angle is desirable to minimize the advance of closing instants as the lubricating oil warms up and the load on the motor decreases. The unexcited type of synchronous motor proved much superior in these respeets to the excited type.

The opening step must be long enough to accommodate the more rapid disturbances, which no mechanical device can hope to follow. The function of the overlap control is then to readjust the opening instant to the optimum point in the opening step. Thus, the slightly faster response of a continuous control has little, if any, advantage over the on-off control described by the authors. Moreover, a continuous control will try to follow the rapid jitter in signal arising from microscopic imperfections in the contact faces, whereas with the on-off control these will be smoothed out by the dead period.

In the absence of contact bounce, and if the voltage across the closing contact is kept below about 10 volts, the erosion of that contact should be negligible. On the other hand, erosion of the opening contact can be substantially eliminated by using a low-impedance by-pass circuit and by keeping the contact current at break below about $0 \cdot 1$ amp. It is virtually impossible to meet the latter condition under all operating conditions without extreme complication.

(*Communicated*): Reference has been made to the harmonics generated by rectifiers in the a.c. supply network. It is of interest to remember that the mode of operation of the contact rectifier described by the authors presupposes a sinusoidal

* READ, J. C., and GIMSON, C. F.: Paper No. 1939 U, October, 1955 (see 102 A, p. 645).

a.c. supply voltage. However, when a number of rectifiers are supplied by a common feeder, the flow of harmonic currents through the reactance of the feeder distorts the voltage at the terminals of the rectifier. This distortion retards in time the instants at which the phase voltages intersect, and therefore the instants when commutation will normally begin. Since the instants at which the contacts close are not similarly retarded, the contacts will close with a negative voltage across them—a condition which may adversely affect the performance of the rectifier. This retardation is a function of the load on the rectifiers, and normally becomes serious only during overload conditions. However, in installations which have a high primary reactance, the retardation may occur at much lower loads. The effect is also dependent on the number of phases of the installation. The retardation becomes less as the number is increased, but the load at which retardation begins is also reduced.

Dr. G. J. Lewis: For electrolytic service the dependability of a rectifier is quite as important as the conversion efficiency which it achieves, since most electrolytic cells are adversely affected by interruptions in the d.c. supply, however short these may be. Moreover, the operation of a battery of cells is necessarily integrated with the running of dependent plants which process the products of electrolysis, so that a current interruption causes repercussions throughout a whole factory and could, in certain circumstances, have costly or dangerous consequences.

Although the equipment described by the authors includes devices which are designed to ensure continuity and steadiness of the d.c. output, it is not clear how effectively these safeguards would deal with voltage fluctuations of the type and magnitude commonly experienced in a public supply network having overhead transmission lines.

Dr. J. C. Read and **Mr. C. F. Gimson** (*in reply*): Mr. Corbyn gives an interesting review of a contact rectifier which has two contacts in series per phase. So far as we are aware, only a single maker employs this arrangement, and it seems probable that it was adopted, not in order to have two contacts in series, but to allow the designers to take advantage of their change to single-way comreactors, by closing the contact when the voltage across it is small. As explained in Section 3.1, it produces in this respect the same result as the cam described in the paper but with considerable extra complication, and the fact that there are twice as many contacts and high-speed mechanisms to look after seems to us to be a disadvantage. We agree completely with Mr. Smith's comments on this matter.

Mr. Corbyn's statement that with the double-contact arrangement the transfer of contact material occurs mainly on the 'make' contact is interesting, as it would seem from this that a relatively crude method of producing the closing step is adopted in the design cited, thus no doubt going some way to compensate for the higher complication and cost that result from the doubling of the mechanical unit.

The ability to ride through a sudden fall of supply voltage depends partly on the volt-ampere characteristic of the back-e.m.f. of the load supplied by the rectifier (since, with all arrangements, if reverse current flows a backfire will be produced), and partly on the length of the opening step and the point in this opening step at which the contact has been set to open. Consequently, the survival of a sudden fall of supply voltage is without meaning unless all these factors are defined. However, for equal expenditure on length of opening step we believe there is nothing to choose with respect to this characteristic between the double-contact arrangement described by Mr. Corbyn and the single-contact arrangement described in the paper, since single-way comreactors are employed in both cases.

The function of the small polarity generator shown in Fig. 8 is to verify that the unexcited synchronous motor (Section 3.2.2) has pulled into step with correct polarity when starting up.

We did not experiment with the 6-phase single-way circuit. If this circuit had been adopted, correct load sharing between the two halves could have been produced by a modification to the circuit shown in Fig. 15.

We agree with Dr. Lewis's remarks. The possible effect of system disturbances is one of the factors which have to be taken into account when comparing contact and semi-conductor rectifiers for high-power electrolytic service.

621.313.334

Paper No. 2180 U
Dec. 1956

AN ASYMMETRICAL INDUCTION-MOTOR WINDING FOR 6 : 3 : 2 : 1 SPEED RATIOS

By Prof. G. H. RAWCLIFFE, M.A., D.Sc., Member, and B. V. JAYAWANT, B.Eng., Graduate.

(*The paper was first received* 9*th March, and in revised form* 11*th July,* 1956.)

SUMMARY

An earlier paper has described a very successful pole-changing winding for 3 : 1 speed ratio; which, however, had the disadvantage of needing eleven control leads and a slightly complicated controller. A new winding is here described[1] which needs only six control leads and a very simple controller, and which gives greater flexibility in the relative ratings at the two speeds. In addition, this winding can be made to operate efficiently at a third speed, using only nine control leads altogether, giving three speeds in the ratio 6 : 3 : 1, and at a fourth speed using thirteen control leads, giving four speeds in the ratios 6 : 3 : 2 : 1. The methods of obtaining the third and fourth speeds are described in the latter part of the paper.

Besides being very successful in operation, this asymmetrical winding has a number of unusual theoretical features of very great interest. It is a working testimony to the possibility of permitting various forms of asymmetry and unbalance in electrical machinery without detriment to its operation.

LIST OF SYMBOLS

n_1 = Total number of conductors in each group of three slots in the 4-pole winding.
n_3 = Number of conductors per slot in the 'extra' 12-pole phases.
V = Line voltage.
V_3 = Voltage per phase in 12-pole operation.
f = Frequency.
Φ_1 = Flux per pole in 4-pole operation.
Φ_3 = Flux per pole in 12-pole operation.
B_1 = Flux density in 4-pole operation.
B_3 = Flux density in 12-pole operation.
i_A, i_B, i_C = Instantaneous phase currents in 12-pole operation.
I_{rms} = R.M.S. magnetizing current in 12-pole operation.
x = One 'step', of $n_1/4$ current-conductors, in the 12-pole m.m.f. waveform.
θ = Electrical angle, rad.
m = Order of harmonic.

Throughout the paper the terms 'asymmetrical' and 'symmetrical' are taken to refer to the geometrical forms of 3-phase circuits and windings, whereas the terms 'unbalanced' and 'balanced' refer to the Fourier fundamental components of the e.m.f.'s and m.m.f.'s produced by these windings. A winding may thus be asymmetrical but balanced, or asymmetrical and unbalanced. If it is symmetrical, however, it must also be balanced.

(1) INTRODUCTION

Earlier papers[2,3] have described the principles and operation of a satisfactory 12 : 4 pole-changing winding, with overall properties superior to any previously developed. At the higher speed, only two-thirds of each phase (80° out of 120° spread) were in circuit, but the winding arrangement was completely symmetrical at both speeds. The principal disadvantage of this winding was that it needed eleven control leads; and there was also no flexibility between the two ratings, though both were high in relation to a particular frame. For example, it was not possible, with this original 3 : 1 pole-changing winding, to increase the 4-pole rating, at the expense of 12-pole rating, for some application needing the highest speed for most of the time with only very occasional low-speed running.

The new winding here described needs only six leads for 3 : 1 pole changing, and it permits great flexibility in the relative ratings at the two speeds. Test results have shown that it is throughout satisfactory in practice; and, besides this, the winding —which is asymmetrical in form at the lower speed—possesses a number of features of unusual theoretical interest

(2) PRINCIPLES OF THE WINDING FOR 3 : 1 SPEED RATIO

(2.1) Basic Theory and Connections

If a standard 3-phase 4-pole delta-connected winding is opened at one corner, it can be fed in series to form one phase of a 12-pole winding. If two other 12-pole windings, of normal pitch and suitably disposed, are wound in the same stator, the three windings together will give a 12-pole rotating field, whereas the first winding used normally, alone, gives a 4-pole rotating field. This is the basis of the pole-changing winding here discussed.

The particular feature of this winding is the novel method of distributing and interconnecting the conductors in the 4-pole winding, and of relating these conductors to those in the 12-pole phases; the objects served being to reduce the number of control leads, to avoid crawling if switched directly into the higher speed, and to obtain the highest possible ratings at the two speeds combined with the greatest relative flexibility between these ratings.

The 3-phase 12-pole winding is necessarily asymmetrical in form, and the paper is of special theoretical interest in that it develops the conditions for a winding of asymmetrical form and uneven distribution to operate as a balanced winding and to take an almost balanced current.

The two alternative circuit arrangements are shown in Figs. 1(*a*) and 1(*b*), the latter being the one tested most exhaustively by the authors, though both were considered, as both have possible applications. In each case only six points in the winding, as marked, need to be brought out to control leads. (For experimental purposes more were originally made available.) To change the speed it is only necessary to switch the three input leads from the points l_1, l_2 and l_3 to the points L_1, L_2 and L_3, and to open or close one contact shown by the points X.

(2.2) Winding Distributions

The general arrangement of the coils forming the winding is shown, in principle, in Fig. 2. In this prototype there were

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
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Mr. Jayawant was formerly at the University of Bristol, and is now with the Metropolitan-Vickers Electrical Co., Ltd.

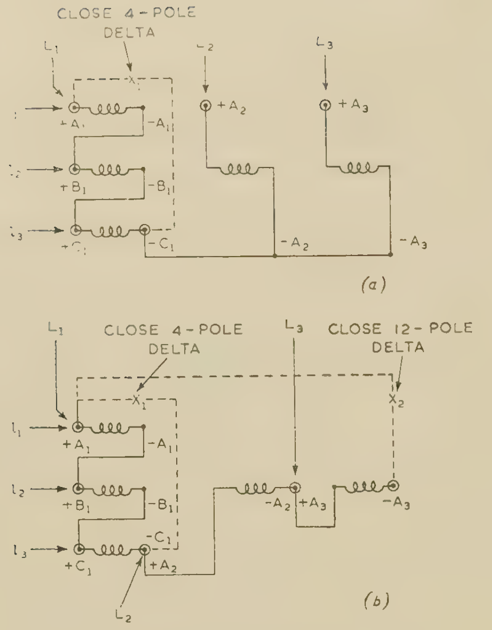

Fig. 1.—Circuit connections—4/12 poles.

(*a*) 4-pole delta: 12-pole star.
(*b*) 4-pole delta: 12-pole delta.
⊙ Control leads.
4-pole inputs l_1, l_2, l_3: 12-pole inputs L_1, L_2, L_3.

winding, so that one-quarter of the total number of conductors per phase band was situated in each outer slot and one-half in the central slot. This permitted conductors of comparable—but not equal—gauge to be used in all the slots of the 4-pole winding.

The distribution in each three slots of n_1 conductors of the 4-pole winding is shown in Fig. 3, and having settled this distribution upon a reasonable but—in principle—arbitrary basis, it then remained to determine, for a given number of such conductors n_1, what number of conductors, n_3, must be used in each slot of the two extra 12-pole phases in order to produce an effectively balanced 12-pole winding.

(2.3) Conductor Ratio between Winding Sections

The conductor ratio, n_3/n_1, between the 4-pole and the 12-pole sections had to be so chosen that when the 4-pole winding was series connected, to form one phase of the 12-pole winding, the e.m.f. induced in this phase was the same as in the other two phases which were directly wound for 12-poles. The ratio had also to be chosen, if possible, so that the fundamental component of the m.m.f. exerted by the series-connected phase was the same as the fundamental component of the m.m.f. exerted by the other phases. The ideal—which fortunately was capable of being realized—was that both conditions should be simultaneously fulfilled.

(2.3.1) Condition for Balanced E.M.F.'s with Special Spread Used.

The voltage V_3 in the first phase when series-connected is shown by the vector diagram in Fig. 4. There are three vectors

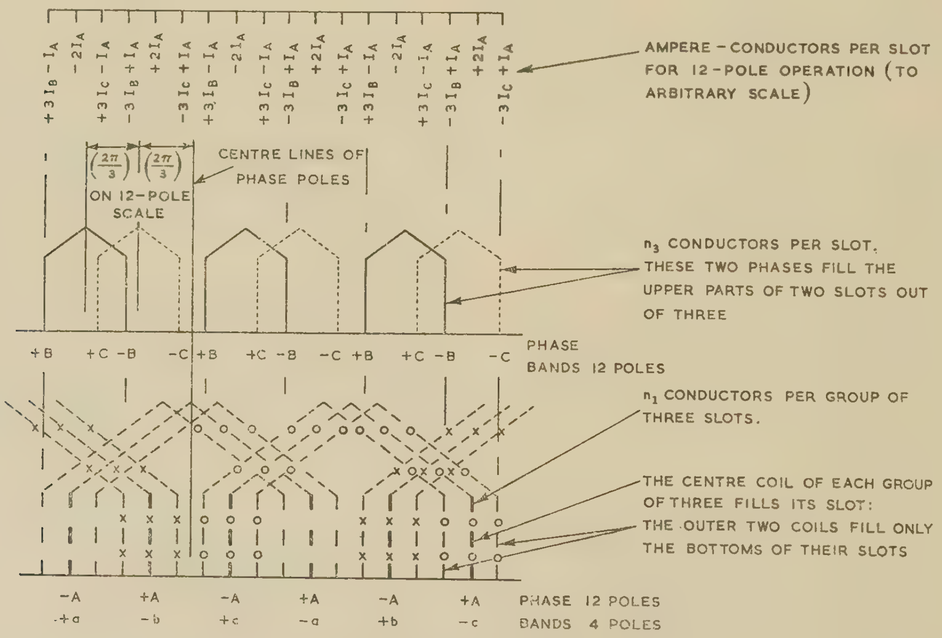

Fig. 2.—Distribution of coil sides and phase bands for 12/4 poles.
Only 18 slots, i.e. half total winding, shown.

3 slots per pole per phase; and it would always be necessary, in machines based on this same principle, to use 3, 6, 9, etc., slots per pole per phase, to give correct angular spacing of the phases for the higher number of poles.

In order that the normal 3-phase 4-pole winding and the two additional 12-pole phases should be included in the same stator frame, it was necessary to modify, in some way, the normal distribution of the 4-pole winding.

It was decided, after preliminary calculations, to alter the distribution of conductors in each 60° phase band of the 4-pole

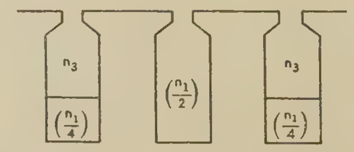

Fig. 3.—Distribution of conductors in each set of three slots.
The $n_1/4$ conductors in the outer slots are rather thinner than those in the centre slot. Hence they fill less than half the slot.

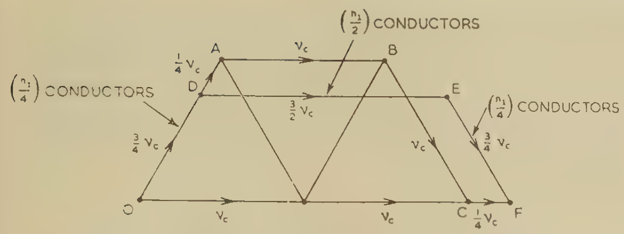

Fig. 4.—Spread factor for special winding distribution: 12 poles.

Windings effectively full pitched.
E.M.F. induced in $n_1/3$ conductors in one slot: V_c.
Vector diagram of e.m.f.'s for uniform distribution: OABC.
Vector diagram of e.m.f.'s for distribution used: ODEF.

$$\left.\begin{array}{l}\text{Spread factor uniformly distributed} = \dfrac{OC}{3\,OA} = \dfrac{2}{3}\\ \text{Spread factor of winding used} = \dfrac{OF}{3\,OA} = \dfrac{3}{4}\end{array}\right\}\ \begin{array}{l}\text{Improvement factor due to greater concentration}\\ = \dfrac{OF}{OC} = \dfrac{9}{8}\end{array}$$

covering, as would be the case for a uniformly spread winding, an angle of 180°, but the vectors are of unequal length. By reference to Fig. 4, it is clear that the total induced e.m.f., for the same total number of conductors, is increased in the ratio 9 : 8 by the concentration of $n_1/2$ conductors in the centre slot, leaving only $n_1/4$ conductors in the outer slots, instead of having $n_1/3$ conductors in each slot.

Thus, for the first phase when series-connected, the induced e.m.f. is given by

$$V_3 = \frac{\pi}{\sqrt{2}}\Phi_3 fp\left[n_1 \times \frac{\sin\dfrac{\pi}{2}}{3\sin\dfrac{\pi}{6}}\right] \times \frac{9}{8}$$

$$= \frac{\pi}{\sqrt{2}}\Phi_3 fp\left(n_1 \times \frac{2}{3}\right) \times \frac{9}{8}$$

and, for the extra phases, the induced e.m.f. is given by

$$V_3 = \frac{\pi}{\sqrt{2}}\Phi_3 fp(n_3 \times 1)$$

where p = Number of poles.

Equating these voltages we have

$$n_3 = \frac{3}{4}n_1$$

$$n_1 = \frac{4}{3}n_3$$

as the condition of equality between the fundamental components of the e.m.f.'s in the three phases.

(2.3.2) Condition for Balanced M.M.F.'s with Special Spread Used.

The waveform of m.m.f. due to the first phase when not uniformly distributed is shown in Fig 5. The fundamental component is there given by $3n_1/2\pi$ turns per pole. Equating this to the fundamental component of the m.m.f. of the extra phases, which is $4n_3/2\pi$, it again follows that

$$n_1 = \frac{4}{3}n_3$$

It was thus possible simultaneously to balance fundamental e.m.f.'s and fundamental m.m.f.'s; with the entirely favourable result that the part concentration of the n_1 conductors reduces the number required in the ratio 9 : 8.

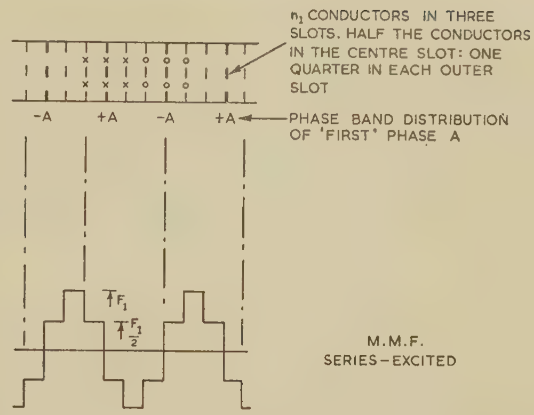

Fig. 5.—M.M.F. for 'first' phase A, 60° spread, series-connected.

Peak of fundamental component $= \dfrac{3F_1}{\pi}$

(2.4) Gauges of Wire and Sizes of Slots

The largest gauge of wire for which there is room will naturally be used in the centre slots. If the remaining conductors of the 4-pole winding are of equal gauge, they will occupy half of each outer slot, leaving only half the area of these slots for the extra 12-pole phases. A better thermal balance will be obtained by reducing the gauge of the $n_1/4$ conductors of the 4-pole winding which lie at the bottom of the outer slots; since there are fewer 4-pole conductors in each outer slot than in each centre slot, it seems reasonable that they should be of higher resistance. This allows the gauge of the n_3 12-pole conductors in each outer slot to be proportionately increased; and in the prototype machine these n_3 conductors occupied two-thirds of each outer slot, and the $n_1/4$ conductors of the 4-pole winding occupied one-third of each outer slot. This division of space is arbitrary, and any other reasonable division would be permissible.

It would, of course, be possible to punch the outer slots rather deeper or wider than the centre slots, provided that the centre-lines of the slots were not displaced. This would permit an almost indefinite amount of relative adjustment between the various wire gauges used for the winding, but would involve special manufacturing arrangements to produce the punchings. These might be justified for a large batch of machines, but it was impracticable to try this variant in the prototype model.

The 4-pole conductors were placed at the bottom of the slot, and the 12-pole conductors at the mouth of the slot. This gives a lower value for 12-pole leakage reactance, and is the arrangement preferred, but it is possible to interchange the sets of conductors, improving the 4-pole performance a little at the expense of the 12-pole performance. This was actually tried experimentally, the coils being interchanged and the machine retested on light load and short-circuit. The difference in performance, though of the kind expected, was numerically very small, and no further investigations of this variant were warranted. Further, it was more difficult to wind the machine with the small coils at the bottom of the slots.

(3) EXTENSION OF USE TO 6 : 3 : 2 : 1 SPEED RATIOS

(3.1) Operation at 2-Pole Speed

The 4-pole winding already developed as part of the winding of this machine is almost a standard 4-pole single-layer winding, though with the special feature that the conductors in each 60° phase band are partly concentrated in the centre slot of each group of three. Any 4-pole full-pitch winding can be converted into a 2-pole winding by reversing alternate coil groups in each

phase, this procedure being a well-known and standard one, and a variety of phase interconnections being used to effect this result. The part concentration of the conductors does not in any way upset this possibility. Since the 4-pole winding is connected in delta, it is convenient to use parallel-star connection for 2-pole operation in this machine. A very satisfactory feature is that this arrangement only requires three additional leads out, and an extremely simple controller, to add a third speed to the original two speeds. The three extra leads, as usual in such 2 : 1 pole-changing windings, are connected to the centre of each phase.

A less fortunate feature is that, if switched from standstill into the 2-pole position, the machine may, in certain circumstances, tend to crawl—a well-known property of single-layer 60°/30° spread 2 : 1 pole-changing windings. In practice, this tendency is easily side-stepped by arranging a simple mechanical interlock, of the well-known type, to prevent the stator being thrown into the 2-pole position without first going into the 12-pole and 4-pole positions, or at least into the latter. The 4-pole connection will carry the machine far above a speed of 428 r.p.m., which is the seventh-harmonic crawling speed of the 2-pole connection. The authors have under consideration a novel arrangement to eliminate seventh-harmonic crawling possibilities in this winding, but this will be considered separately. For practical operation, and for the purposes of the paper, the interlock suggested would be quite sufficient.

(3.2) Operation at 6-Pole Speed

In the preceding Section it was explained that each phase of the 4-pole winding could be connected with two paths in parallel, so as to halve the number of poles. The resultant 2-pole 3-phase winding may then be series connected, to give a single-phase 6-pole winding. This arrangement is shown in Fig. 6(*a*). The three 6-pole phases are connected in star, both because this gives a reasonable value of flux density in the machine for 6-pole operation, as is shown in Section 4, and also because there is some unbalance in this connection, as explained in Section 5, and the unbalance is less objectionable in star than in delta connection.

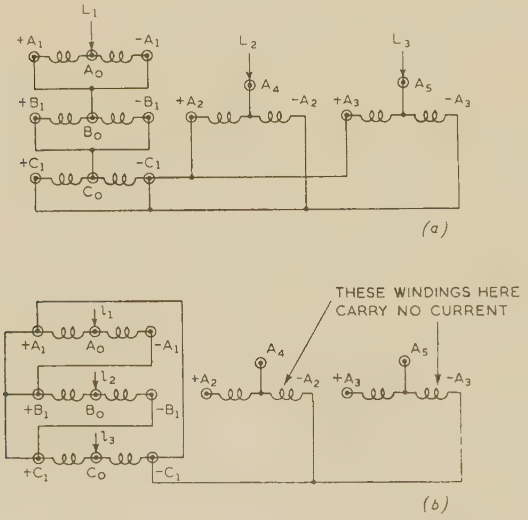

Fig. 6.—Circuit connections—2/6 poles.

(*a*) 6-pole parallel-star.
(*b*) 2-pole parallel-star.
⊙ Control leads.
2-pole inputs l_1, l_2, l_3: 6-pole inputs L_1, L_2, L_3.

The spread factor of the 2-pole 3-phase winding when series-connected to give a 6-pole single-phase winding is different from that obtained when the 4-pole winding was series connected to give 12 poles. The latter spread factor was shown in Section 2.3.1 and Fig. 4 to be 3/4. The 6-pole spread factor is given by a comparable construction shown in Fig. 7, extending over only half the angular spread, which was formerly 180° and is now 90°.

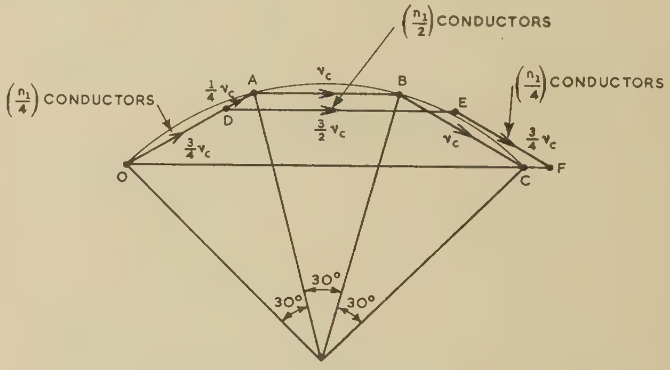

Fig. 7.—Spread factor for special winding distribution parallel-connected for 6-poles.

Windings effectively half pitched.
E.M.F. induced in $n_1/3$ conductors in one slot: V_c.
Vector diagram of e.m.f.'s for uniform distribution: OABC.
Vector diagram of e.m.f.'s for distribution used: ODEF.

$$\text{Spread factor uniformly distributed} = \frac{OC}{3OA} = \frac{\sqrt{3}+1}{3}$$

$$\text{Spread factor for special distribution} = \frac{OF}{3OA} = \frac{2+\sqrt{3}}{4}$$

From Fig. 7 it will be seen that the spread factor of the resultant single-phase 6-pole winding is $(\sqrt{3}+2)/4 = 0{\cdot}933$, whereas for 12 poles the same winding had a spread factor of $3/4 = 0{\cdot}75$.

A chording factor of $1/\sqrt{2}$ has, of course, been introduced by changing from 4 to 2 poles, and this must be taken into account when relating the phase e.m.f. to the effective number of turns per phase. Using these spread and chord factors it is possible to calculate the phase e.m.f. of the first 6-pole phase.

The two extra 12-pole phases, being of the normal type, can be connected by the same parallel arrangement into two extra 6-pole phases, but since all the conductors per coil group are in the same slot, the spread factor is unity in both cases. The chord factor for the extra 6-pole phases is again $1/\sqrt{2}$, as for the first 6-pole phase.

(3.3) Winding Diagram of Final Machine

The final winding diagram is shown in Fig. 8. It will be seen that the phases are spaced by $4\pi/3$ in the initial layout of both the first phase and the extra phases, as is usual in 2 : 1 pole-changing windings. The coil groups in the extra phases can be arranged in two different ways, but for convenience in manufacture, avoiding fouling between the coil noses, it is best to arrange the coils so that the noses of the larger coils lie in the clear spaces between those of the smaller coils.

It is a fortunate circumstance that the reconnection of the first phase, either in series for four poles or in series-parallel for two poles, must leave the phase direction of this phase unaltered with respect to those of the extra phases when they are all connected for the corresponding number of poles. The circuit connections for 2/6 poles are shown in Fig. 6, and it will be seen that if $-A_2$, $-A_3$ and $-C_1$ are connected to form the star point for 12-pole operation, as shown in Fig. 1(*a*), this point has not to be broken when changing to 6 poles. All that is necessary is to connect $+A_2$ and $+A_3$ also to $-C_1$, and to attach the supply leads to the centre points of the extra phases,

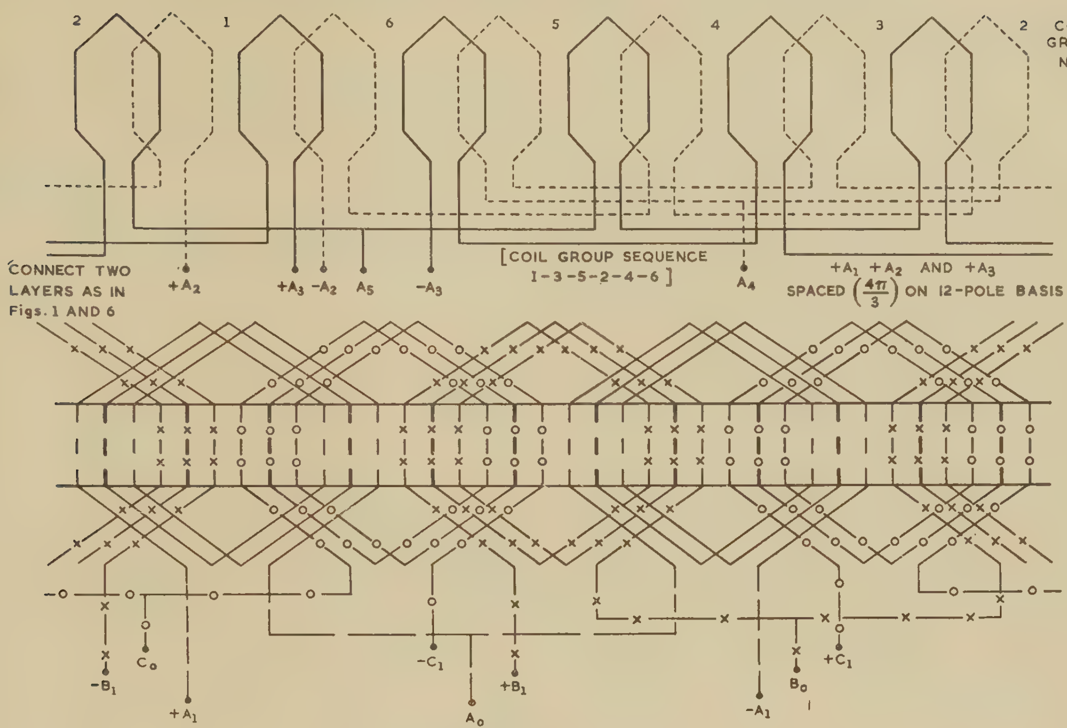

Fig. 8.—Winding diagram for 2/4/6/12 poles.

$+A_1$, $+B_1$ and $+C_1$ spaced $\frac{4\pi}{3}$ on 4-pole basis.

as shown in Fig. 6(*a*). A similar type of reconnection is necessary if the 12-pole connection is in delta, as in Fig. 1(*b*), though in this case $-A_2$ and $-A_3$ are connected back to $-C_1$. In all circumstances, as shown in Figs. 1 and 6, 13 leads only are necessary to obtain 4 speeds.

(4) RELATIVE MAGNETIC LOADINGS AT THE FOUR SPEEDS

Taking the basic equation that

$$\text{Flux per pole} \propto \frac{\text{Voltage per phase}}{\text{Effective conductors per phase}}$$

and applying it to 4-pole operation in delta, it follows that

$$\Phi_1 \propto \frac{V}{4n_1 \times 3/\pi} = \frac{V\pi}{12n_1}$$

It is assumed that the unequal distribution of the n_1 conductors over the 60° phase spread produces no sensible alteration in the distribution factor relative to 4 poles; in fact, as can be easily shown by methods similar to those of Fig. 5, the difference is about 1%, which is here ignored.

Applying the same general relation to 12-pole operation, in delta, the result is obtained that, for the first series-connected phase,

$$\Phi_3 \propto \frac{V}{12n_1 \times \frac{9}{8} \times \frac{2}{3}} = \frac{V}{9n_1}$$

As has been shown in Sections 2.3.1 and 2.3.2, the ratio 9 : 8 is the ratio of increase in the distribution factor, relative to 12 poles, owing to part concentration of the conductors in the central slot of each group of three; and 2/3 is the normal distribution factor for uniform spread over 180° in three slots.

Similarly it follows, for the extra 12-pole phases, that

$$\Phi_3 \propto \frac{V}{12n_3}$$

since these n_3 conductors are all concentrated in one slot per pole per phase. As shown in Sections 2.3.1 and 2.3.2, the two values of Φ_3 obtained here are identical, since $n_1 = 4n_3/3$.

Taking the ratio of the fluxes it follows that, when the winding is connected in delta for both speeds, $\Phi_3/\Phi_1 = 4/3\pi$ and hence that $B_3/B_1 = 4/\pi = 1{\cdot}27$. If the machine is connected in star for 12-pole operation only, as it readily can be, the ratios in this case are $\Phi_3/\Phi_1 = 4/3\pi\sqrt{3}$; and hence $B_3/B_1 = 4/\pi\sqrt{3} = 0{\cdot}735$.

There is therefore a simple option between having the highest possible flux density at the 12-pole speed, and 79% of this flux density at the 4-pole speed; or having the highest possible flux density at the 4-pole speed, and 74% of it at the 12-pole speed. The choice can only be made when the duty is known, but only six leads are required in either case, as shown in Figs. 1(*a*) and 1(*b*).

The use of the 4-pole winding as part of the 4/12 pole combination requires that the 4-pole winding be connected in series-delta, thus making parallel-star the obvious connection for use in 2-pole operation. As is well known, the flux density on making the change from 4 to 2 poles is reduced in the ratio $1/\sqrt{2} = 0{\cdot}707$, when the phase spreads in the 4- and 2-pole connections are, respectively, 120° and 60°. For phase spreads of 60° and 30° respectively, the change of flux density is in the ratio

$$\frac{1}{\sqrt{3}}\,\frac{1}{\sqrt{3}-1} = 0{\cdot}787$$

which is the value for the winding used in this machine.

Although the phase unbalance will make the voltages per phase slightly unequal in the 6-pole connection, it will be sufficient

to assume equality for the purpose of estimating the relative flux densities in the various connections. In changing from 12 to 6 poles a chording factor of $1/\sqrt{2}$ is introduced, and the conductors are connected in two parallel paths, but the area of each pole is doubled. In both cases, in this machine, the spread factor of the extra phases is unity, as the machine has one slot per pole per phase in the 12-pole connection. The overall result is to increase the flux density in the ratio $\sqrt{2}$, for the same applied voltage per phase, when changing from 12 to 6 poles. This, in fact, slightly overestimates the flux because, as shown in Section 5, the extra phases have fewer turns in their windings than would be ideal for 6-pole operation. Hence the phase voltage is less than the nominal line-to-neutral value.

It follows from the arguments of this Section, taken together, that for operation at a given line voltage on 2/4/6/12 poles, respectively, connected parallel-star/delta/parallel-star/delta, the flux densities will be in the ratios 0·79 : 1 : 1·04 : 1·27; but that, for connection in parallel-star/delta/parallel-star/star, the ratios will be 0·79 : 1 : 1·04 : 0·735. The extent to which this theory is borne out in practice is seen in Section 7.2, which gives the magnetizing curves obtained on test. It is clear that, for the former set of connections, the maximum line voltage will be fixed by the 12-pole flux density, and that it will be lower than the voltage for the latter set of connections. Accepting the fact, explained above, that the flux density on 6 poles is rather less than the nominal relative figure of 1·04, it follows that the line voltages must be in the ratio 1·27 : 1 = 380 : 300 for the two sets of connections.

(5) UNBALANCE IN THE 6-POLE CONNECTION

The operation of the machine in 2-, 4- and 12-pole régimes used the winding in an asymmetrical but balanced connection. The 6-pole connection is not only asymmetrical but unbalanced. This will be seen from considering the 6-pole e.m.f.'s and m.m.f.'s, as follows, in the same way as the corresponding 12-pole quantities were considered in Section 2.3.

(5.1) Condition for Balanced E.M.F.'s

If the fundamental e.m.f.'s in the first 6-pole phase and the extra 6-pole phases are to be made equal, it follows, by equating effective conductors in series, that

$$6n_1 \times \frac{\sqrt{3}+2}{4} \times \frac{1}{\sqrt{2}} = 6n_3 \times 1 \times \frac{1}{\sqrt{2}}$$

i.e.

$$\frac{n_3}{n_1} = \frac{\sqrt{3}+2}{4} = 0{\cdot}933$$

It will be shown in Section 5.2 that the same ratio between n_3 and n_1 is obtained by equating the fundamental components of m.m.f. This compares with the value 0·75 obtained by equating 12-pole e.m.f.'s.

Thus it follows that a winding of this type, if designed to give fundamental e.m.f.'s and m.m.f.'s exactly balanced between all phases for 12-pole operation, will not be exactly balanced when pole-changed for 6 poles. It will not, however, be seriously out of balance, and it was therefore decided to try its operation in practice before proceeding further. It proved entirely satisfactory, giving results recorded in Section 7.3.

(5.2) Condition for Balanced M.M.F.'s

The m.m.f. waveform for the 2-pole winding, when series connected to give six poles, is shown in Fig. 9, the amplitude of the mth harmonic being given

$$a_m = \frac{2F}{m\pi}\left(1 + \cos\frac{m\pi}{6}\right)\cos\frac{m\pi}{4}$$

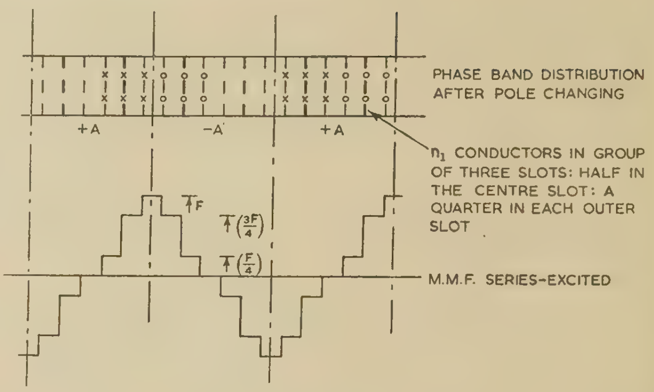

Fig. 9.—M.M.F. for 'first' phase A, pole-changed for 2 poles and series-connected for 6 poles.

Peak of fundamental component $= \frac{2+\sqrt{3}}{\pi\sqrt{2}}F$

The fundamental component of m.m.f. is thus given by $F(2+\sqrt{3})/\pi\sqrt{2}$, where F is the peak amplitude of m.m.f., acting on the centre of the pole, in ampere-turns per pole. It is clear that

$$F = \text{(conductors in three slots)(current)} = n_1 I$$

The m.m.f. waveform of the extra 6-pole phases is shown in Fig. 10.

The fundamental component of m.m.f. can be written as

$$\frac{4}{\pi}\left(\cos\frac{\pi}{4}\right)F$$

where F here is $n_3 I$.

Equating m.m.f.'s it follows that

$$\frac{2+\sqrt{3}}{\pi\sqrt{2}}n_1 I = \frac{4}{\pi\sqrt{2}}n_3 I$$

or

$$\frac{n_3}{n_1} = \frac{2+\sqrt{3}}{4}, \text{ as before.}$$

It thus follows that, for 6-pole operation as for 12-pole operation, the condition for balanced e.m.f. is the same as the condition for balanced m.m.f.; but these conditions are different for the two pole numbers.

(5.3) A Compromise Winding for 6 : 12 Poles

Having found that a machine designed on a 12-pole basis would operate satisfactorily as a 6-pole machine, despite appreciable unbalance of the fundamental component, it became clear

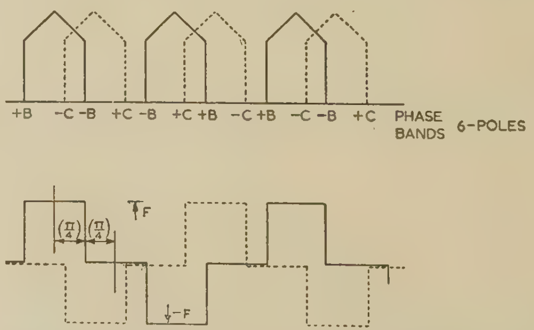

Fig. 10.—M.M.F. waveforms of 'extra' 6-pole phases.

Peak of fundamental component $= \frac{4}{\pi}\cos\frac{\pi}{4}F = \frac{2\sqrt{2}}{\pi}F$

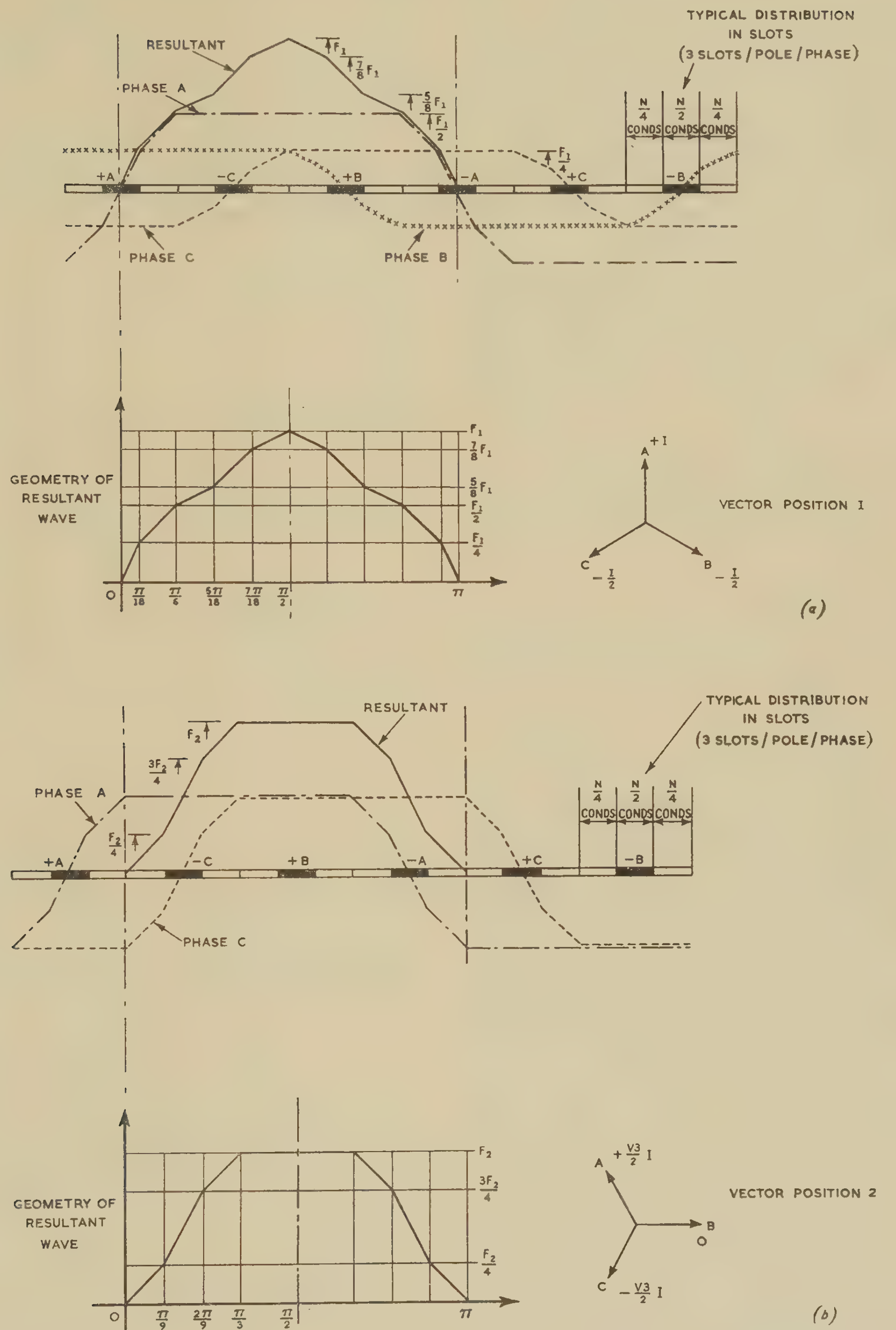

Fig. 11.—M.M.F. waveform obtained by reinforcing the middle of each phase band of a 60° spread 3-phase winding, in the ratio of 2 : 1.

(*a*) The coefficient of the *m*th term in the Fourier series is

$$a_m = \frac{36F_1}{\pi^2 m^2}\left(\sin\frac{m\pi}{9}\cos\frac{m\pi}{18}\cos^2\frac{m\pi}{6}\right)$$

The series is

$$y = F_1(0\cdot921 \sin\theta + 0\cdot0691 \sin 5\theta + 0\cdot0123 \sin 7\theta + 0\cdot00497 \sin 11\theta + 0\cdot0102 \sin 13\theta + \ldots)$$

(*b*) The coefficient of the *m*th term in the Fourier series is

$$a_m = \frac{36F_2}{\pi^2 m^2}\left(\sin\frac{m\pi}{9}\cos\frac{m\pi}{6}\cos\frac{m\pi}{18}\right) = \frac{36F_1}{\pi^2 m^2}\left(\sin\frac{m\pi}{9}\cos\frac{m\pi}{18}\cos\frac{m\pi}{6}\cos\frac{\pi}{6}\right)$$

The series is

$$y = F_1(0\cdot921 \sin\theta - 0\cdot0691 \sin 5\theta - 0\cdot0123 \sin 7\theta + 0\cdot00497 \sin 11\theta + 0\cdot0102 \sin 13\theta \ldots)$$

that the requirement for exact fundamental balance, so often thought to be essential, is actually no more necessary than exact geometrical symmetry. It was therefore decided to wind another machine in which the value of n_3, the number of conductors per slot in the extra phases, was half-way between the values calculated, respectively, for 12-pole and 6-pole phase balance. In the particular machine used, n_3 was ideally 108 and 134 respectively, and the compromise form of the machine had 121 conductors. Tests were taken on this machine, which was slightly unbalanced for both 6 and 12 poles rather than balanced for 12 poles and substantially unbalanced for 6 poles. The test differences between this compromise winding and the original winding balanced for 12 poles were insufficient to be worth recording, except when connected in delta for 12 poles. There was then a net fundamental voltage acting around the delta network causing wasteful heating, and the phase currents were considerably unbalanced, though the line currents were still balanced.

It is thus clear that this compromise winding is undesirable if the machine is to be connected in delta for operation with 12 poles, as the unbalance causes an appreciable circulating current of zero sequence. For operation in star on 12 poles, and for the other three speeds, either winding is equally permissible; though the compromise winding was in no way a sufficient improvement on the initial unbalanced winding to warrant its further consideration.

The general lesson from these tests, however, is that appreciably unbalanced windings may be satisfactorily used in star connection but not in delta connection, whereas balanced asymmetrical windings can be used either in star or in delta.

(6) M.M.F. WAVEFORMS ON 4/12 POLE OPERATION

(6.1) Waveforms on 4-Pole Operation

Whilst it was obvious, from the efficient and quiet operation of the machine in the 4-pole connection, that the non-uniform distribution of this winding had not caused any difficulty in practice, it was thought desirable to complete the analysis by constructing the theoretical waveforms of m.m.f. and examining their harmonic content. Fig. 11(a) shows the m.m.f. waveform for the first of the two current-vector positions usually considered, and the Fourier analysis of this waveform is given in the subcaption. For comparison, it will be helpful to recall that the Fourier analysis for the m.m.f. of a standard winding of uniform spread, for the same current-vector position, has harmonics of relative amplitudes given by the following series:

$$\sin\theta + 0{\cdot}040\sin 5\theta - 0{\cdot}0204\sin 7\theta - 0{\cdot}00827\sin 11\theta + 0{\cdot}00592\sin 13\theta + \ldots$$

The second of the two current-vector positions for which analysis is normally carried out yields the m.m.f. waveform shown in Fig. 11(b), from which it will be seen that the harmonics are, as usual, unchanged in magnitude with change of current-vector position, but that some are reversed in sign, compared with the first current-vector position.

The general conclusion is therefore that the part concentration of the winding in the centre slot of each group of three has increased the 5th and 13th harmonics, but decreased the 7th and 11th harmonics. Since it is rare for any harmonic but the 7th to be troublesome in practice, these revised values of harmonic are, on balance, advantageous. An interesting problem arises, however (which it is intended to pursue separately), about the optimum degree of concentration in the centre slot. Total concentration in the centre slot leads to a 7th-harmonic m.m.f. so large that a machine wound in that way crawls irrevocably;[2] but the moderate degree of concentration used in this machine is actually an improvement upon uniform spread. There must therefore be a turning point in the degree of concentration which would give minimum 7th-harmonic content in the m.m.f. waveform, and it is intended to elucidate this point by both theory and experiment.

(6.2) Waveforms on 12-Pole Operation

The relative ampere-conductor loadings of the machine, in terms of ampere-conductors per slot, can be expressed by the following sequence, repeated indefinitely, as can be seen from Fig. 2.

$$\left|(+3i_B - i_A) : (-2i_A) : (+3i_C - i_A)\right| \quad \longleftarrow \text{Pole pitch} \longrightarrow$$

$$\left|(-3i_B + i_A) : (+2i_A) : (-3i_C + i_A)\right| \quad \longleftarrow \text{Pole pitch} \longrightarrow \quad \text{etc.}$$

Taking the instantaneous currents given by seven successive current-vector positions, at 30° intervals, as shown by Fig. 12(a) starting from the instant when the first phase A has its peak value, the relative ampere-conductor loadings occur in the following sequences:

$(-2\frac{1}{2} : -2 : -2\frac{1}{2} : +2\frac{1}{2} : +2 : +2\frac{1}{2})$ etc., in vector position 1

$\frac{\sqrt{3}}{2}(-1 : -2 : -4 : +1 : +2 : +4)$ etc., in vector position 2

$(+1 : -1 : -3\frac{1}{2} : -1 : +1 : +3\frac{1}{2})$ etc., in vector position 3

$\frac{\sqrt{3}}{2}(+3 : 0 : -3 : -3 : 0 : +3)$ etc., in vector position 4

$(+3\frac{1}{2} : +1 : -1 : -3\frac{1}{2} : -1 : +1)$ etc., in vector position 5

$\frac{\sqrt{3}}{2}(+4 : +2 : +1 : -4 : -2 : -1)$ etc., in vector position 6

$(+2\frac{1}{2} : +2 : +2\frac{1}{2} : -2\frac{1}{2} : -2 : -2\frac{1}{2})$ etc., in vector position 7

etc. etc.

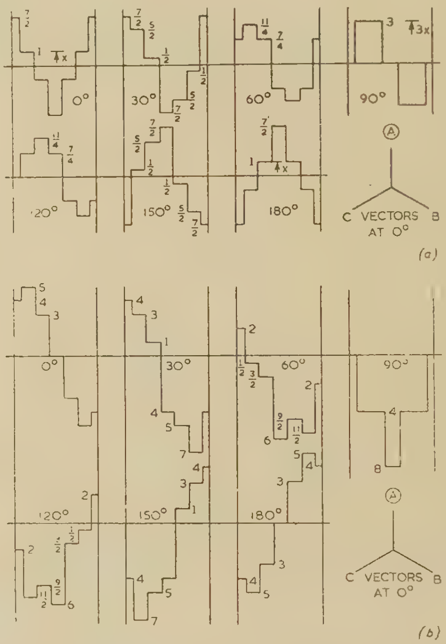

Fig. 12.—M.M.F. waveforms, at 30° intervals, over one half-cycle.
To arbitrary scale.
(a) 12-pole.
(b) 6-pole.
All the 30°, 90° and 150° waves must be multiplied by $\sqrt{3}/2$ to give true heights.

The second six vector positions, of which vector position 7 is the initial one, simply repeat the results of the first six positions in sequence, with reversal of all signs.

In a normal 3-phase winding there are only two limiting geometrical shapes between which the m.m.f. waveform pulsates, and for which Fourier analyses are ordinarily taken; but in this winding, where one phase differs from the other two, there are necessarily four limiting geometrical shapes. These correspond to the first phase being at peak value or at zero value (vector positions 1 and 4, respectively), or to *one* of the extra phases being at peak value or at zero value (vector positions 3 and 2, respectively). Vector positions 5 and 3 are, in principle, similar, and thus give identical ampere-conductor loadings, relatively displaced in space by one slot, equivalent to 60°. Vector position 6 is geometrically equivalent to vector position 2, but the ordinates of the m.m.f. waveform occur in the reverse sequence, which will alter the relative phases of the component harmonics but will leave unaltered their magnitudes, which alone are of importance here. The ampere-conductor loadings over a half-cycle of the supply voltage are plotted in Fig. 6, the waveforms being drawn to the same scale, except that the awkward factor $\sqrt{3}/2$ is extracted from the waveforms given by the current-vector positions 2, 4 and 6. These waves are, in effect, drawn a little over scale, for convenience.

The Fourier analyses of all these waves are given in Appendix 10.2. It will be seen that the magnitudes of the fundamental, and of all harmonics which are not multiples of three, are maintained constant for all vector positions; and that the peak of the fundamental component of the resultant m.m.f. wave is, in every case, given by $9x/\pi$ ampere-turns/pole. The value x is marked on Fig. 12(*a*) and, as will be shown, is given by

$$x = \frac{n_1 I_{rms}}{2\sqrt{2}}$$

By reference to Fig. 12 it will be seen that the height of the step x, measured in ampere-conductors, is equal to *half* the effect of $n_1/2$ conductors, in a central slot, carrying unit current; i.e. to $n_1/4$ ampere-conductors. Hence if $n_1 = 4$ and the peak current is unity, x is equal to one ampere-conductor, and x in general is equal to $n_1 I_{rms}/2\sqrt{2}$. But the ampere-conductors traversed in passing up one side of a pole are, of course, numerically equal to the total m.m.f. acting on the centre of the pole; and the peak fundamental m.m.f. is therefore equal to

$$\frac{9n_1 I_{rms}}{2\sqrt{2}\pi} = 1\cdot 01 n_1 I_{rms} \text{ ampere-turns}$$

The actual number of conductors per pole per phase in the first phase on 12-pole operation is n_1, and in the extra phases it is $n_3 = \frac{3}{4}n_1$. The fundamental m.m.f., in ampere-turns per pole acting on the pole centre, in a normal 3-phase winding is

$$\frac{9\sqrt{2}}{\pi^2} \text{[conductors per pole per phase] } I_{rms}$$

and the expression above may, for comparison, be written

$$\frac{\pi}{4}\frac{9\sqrt{2}}{\pi^2} n_1 I_{rms} = \frac{\pi}{3}\frac{9\sqrt{2}}{\pi^2} n_3 I_{rms}$$

It is thus clear that the n_1 conductors are being used with 78·5% of their normal winding factor, but that the n_3 conductors are connected at 104·5% winding factor—overall, a high average value for a pole-changing winding.

(7) TEST RESULTS

(7.1) Load and Short-Circuit Tests

A machine of the kind discussed in the paper must always be connected in star for 2 poles, in delta for 4 poles and in star for 6 poles; but it may be either in star or in delta for 12 poles.

If star-connected for 12 poles, the limiting voltage is first reached in the 4-pole connection; and, for the experimental machine, this was 380 volts. If delta-connected for 12 poles, the limiting voltage is first reached in this connection; and, for the particular machine, it was 300 volts.

Full-load temperature tests were therefore taken for all pole numbers for two values of line voltage—380 and 300 volts—the 12-pole connection being star in the former case and delta in the latter. The usual short-circuit tests were also performed in all four connections, and the pull-out power was calculated from each of these tests.

The frame in which the special winding was placed was nominally intended for a 5 h.p. 4-pole t.e.f.c. 3-phase induction motor.

The results obtained are shown in Table 1.

Table 1

TEST RESULTS FOR A FOUR-SPEED MACHINE

Connection	Line voltage 380 volts		Line voltage 300 volts	
	Continuous horse-power	Pull-out horse-power	Continuous horse-power	Pull-out horse-power
2-pole parallel-star	5·0	12·7	3·85	7·9
4-pole delta . .	4·3	8·4	3·75	5·2
6-pole parallel-star	2·1	3·5	1·65	2·2
12-pole star 380 volts delta 300 volts	0·65	0·85	0·85	1·55

The continuous ratings obtained are likely to be below the best possible values for the frame, because, in the experimental machine, unusually large winding clearances were allowed in order to be certain that no difficulties would occur in winding the machine, which was done in a general experimental workshop. Winding to systematized industrial processes would be likely to give appreciable improvement in continuous ratings. Further, it would ideally have been desirable to use a frame of rather larger diameter and smaller core length—perhaps one designed for an 8-pole winding—rather than the frame actually used.

It is thought that the 12-pole delta connection using 300 volts gives a better balanced performance overall, especially for a constant-torque load; but the 12-pole star connection using 380 volts might be suitable for a load where the torque rose rapidly with speed.

(7.2) Magnetizing Curves

Magnetizing curves for the four speeds are given in Fig. 13, and it will be seen that the voltages at which saturation occurs in the four connections are approximately in accordance with what would have been expected from Section 4.

As between 4-pole and 12-pole operation, the limiting voltage, 380 volts, is reached with 4 poles when the 12 poles are connected in star; but 12 poles give a limiting voltage of 300 volts when they are connected in delta. The curves for 2 and 6 poles lie close together, as do those for 4 and 12 poles. The currents per phase are larger for 2 and 6 poles, as would be expected, but the currents per conductor are of the same order, since there are two parallel paths in the former case.

(7.3) Phase Balance in 12-Pole Connection

It ought to be recorded that the voltage of the neutral point, when star connection was used, only deviated by 4% from its

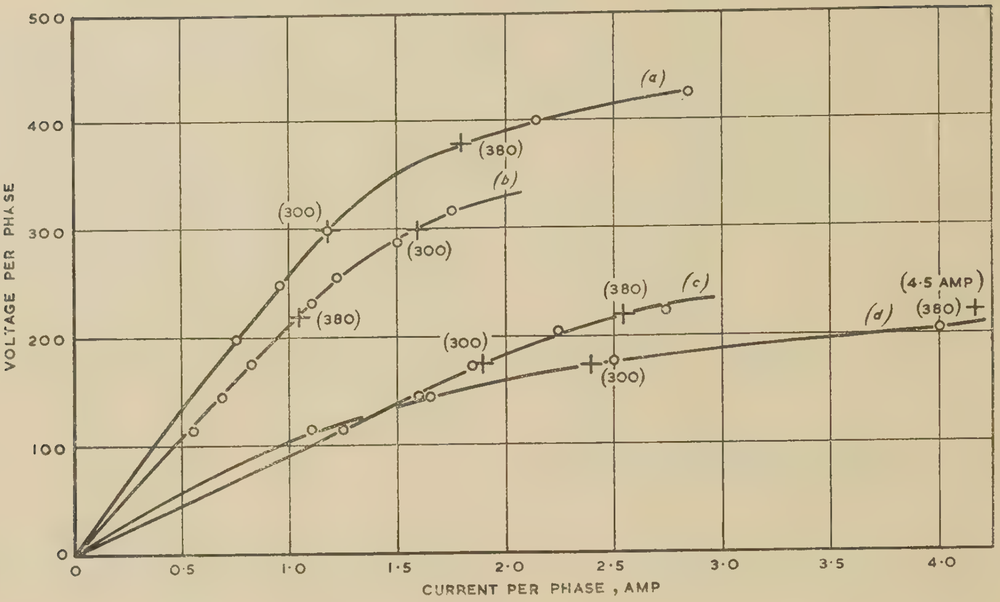

Fig. 13.—Magnetizing curves for 2/4/6/12 poles.

(*a*) No-load current, 4-pole.
(*b*) No-load current, 12-pole.
(*c*) No-load current, 6-pole.
(*d*) No-load current, 2-pole.
+ Operating points at the two specified line voltages: 380 and 300 volts.
Note that the current per conductor is half the current per phase for 6-poles and 2-poles.

true neutral value, which confirmed the analysis of Section 2.3 by which the conductor ratio n_3/n_1 was determined, and it was also found that the magnetizing currents in all three 12-pole phases were equal, to within $\pm 3\%$. In general, the winding acted as a balanced winding to a close degree of accuracy.

In 12-pole delta connection, the phase voltages are necessarily held constant, but it was found experimentally that the currents in all the phases were the same to within $\pm 8\%$, over the whole ranges of voltage and current. When it was first decided to test the delta connection, some apprehension was felt about possible large circulating currents at harmonic frequencies, but fortunately this fear proved to be almost groundless. The 12-pole winding is, in fact, an asymmetrical but balanced winding.

(8) CONCLUDING NOTE ON POLE-CHANGING WINDINGS

Pole-changing windings necessarily fall between two limiting types: those in which all the conductors are used at each speed, and those in which the conductors used at one speed are wholly unused at the other speeds. The former, where advantageously possible, is the obviously desirable type; the latter may be inevitable for some speed ratios. A 4-speed machine, for example, of 2/4/6/12 poles has hitherto normally had one winding for 2/4 poles, and another winding for 6/12 poles; the 2 : 1 speed ratio being the most familiar pole-changing arrangement. Each of these windings, taken alone, is of the first type; the two together are of the second type with respect to one another.

Very little has been done by way of developing windings of an intermediate type, in which not all of the windings are used for all speeds, but in which all of the windings are used for some speeds and most of them are used for all speeds. This would clearly be a substantial advance towards the ideal, as compared with a separate winding for one or two speeds only. The winding here devised for 2/4/6/12 poles uses all the windings at the two lower speeds, but only their major part at the two higher speeds. However, as the rating conditions are always less severe at the higher speeds, this is a better alternative than if all the windings were used at the higher speeds, and a part only at the lower speeds; and the distribution of the copper which is used is favourable from the point of view of good cooling.

This winding seems to exemplify a general principle which might be more extensively used, for the idea of using part windings for pole changing does not appear to have been exploited. Besides permitting improved power ratings, this principle may also reduce the complexity of control arrangements and make possible higher magnetic loadings and torques than could otherwise have been obtained. The exact benefit to be gained cannot be exactly computed from experiments on a very few machines, but it seems likely that at least 15–20% improvement on average rating, for any three- or four-speed machine compared with a similar machine in the same frame with two separate windings, can be reasonably expected by using the arrangements proposed in the paper.

(9) REFERENCES

(1) British Patent Application No. 04617. 1956.
(2) RAWCLIFFE, G. H., and JAYAWANT, B. V.: 'The Development of a New 3 : 1 Pole-Changing Motor', *Proceedings I.E.E.*, Paper No. 1958 U, December, 1955 (**103** A, p. 306).
(3) RAWCLIFFE, G. H., and MCDERMOTT, B. C.: 'The Theory of Third-Harmonic and Zero-Sequence Fields', *ibid.*, Monograph No. 157 U, December, 1955 (**103** C, p. 212).

References 2 and 3 contain full bibliographies of earlier related work, and can be consulted if desired. This paper is really an extension of Reference 2, and it has therefore been thought unnecessary to repeat the Bibliography given there.

(10) APPENDICES

(10.1) Fourier Analyses of Complex M.M.F. Waveforms: A Reduction Formula

In determining the m.m.f. waveforms of such waves as are shown in Fgs. 11 and 12 a great deal of algebraic working may

be necessary. The labour involved can be drastically reduced for most machine waveforms, which are symmetrical about the centre point of each half-cycle, by the use of a reduction formula. In Fig. 14 a shortened trapezoidal waveform is shown, of which

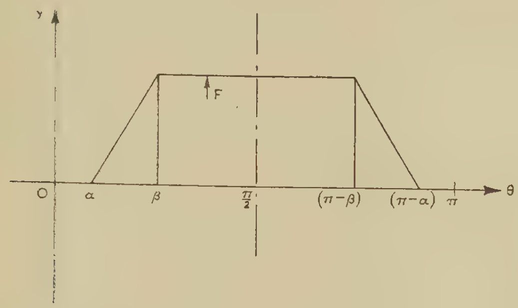

Fig. 14.—Generalized trapezium for Fourier analysis.

$$a_m = \frac{8F}{m^2\pi(\beta - \alpha)} \sin \frac{m(\beta - \alpha)}{2} \cos \frac{m(\beta + \alpha)}{2}$$

or

$$a_m = \frac{4F}{m^2\pi} \frac{\sin m\beta - \sin m\alpha}{(\beta - \alpha)}$$

the Fourier analysis can be proved, by the usual methods, to be given by either of the expressions beneath the Figure, where a_m is the amplitude of the mth harmonic. [$m = 1, 5, 7, 11, 13$, etc. (only) for any symmetrical 3-phase winding: triplen harmonics are excluded.] Almost any stepped waveform, however complicated, can be dissected into a number of trapezoidal strips, as an inspection of Figs. 11(a) and 11(b), for example, will show clearly.

A rectangle is, of course, a particular case of a trapezium, and an isosceles triangle is simply a regular trapezium with one of the parallel sides equal to zero. If, therefore, we give special values, as shown in Table 2, to α and β in the above expressions, we can obtain the Fourier series for all the types of waveform shown. In obtaining some of these results it is convenient to use the first form of a_m, although it is slightly more complicated, because it avoids the occurrence of indeterminate expressions.

It might be added that, since it is known that m can only take the particular values stated above, there are certain identities which can assist in reducing still more the labour involved in using these reduction formulae. The identities include:

$$\cos^2\left(\frac{m\pi}{6}\right) = \frac{3}{4} \qquad \sin^2\left(\frac{m\pi}{6}\right) = \frac{1}{4}$$

$$\cos\left(\frac{m\pi}{3}\right) = \frac{1}{2} \qquad \sin^2\left(\frac{m\pi}{3}\right) = \frac{3}{4}$$

$$\cos^2\left(\frac{m\pi}{3}\right) = \frac{1}{4}$$

The Fourier analyses of all the waveforms in the paper, except the asymmetrical ones in Fig. 12, can be written down with very little labour indeed by the use of these general reduction formulae, and it is thought that this generality makes it worth recording them for possible application elsewhere.

(10.2) Fourier Analysis of M.M.F. Waveforms in 12-Pole Operation

All the waveforms to be considered are shown, with all relevant data, in Fig. 18(a).

The m.m.f. waveform due to the currents in vector position 1 can be shown, by the usual methods, to be

$$\frac{9}{\pi}x\left(\sin\theta - \frac{2}{3} \times \frac{1}{3}\sin 3\theta + \frac{1}{5}\sin 5\theta + \frac{1}{7}\sin 7\theta - \frac{2}{3} \times \frac{1}{9}\sin 9\theta + \frac{1}{11}\sin 11\theta + \ldots\right) \text{ etc.}$$

the amplitude of the resultant wave being given by $7x/2$. Hence the fundamental peak is $18/7\pi$ (resultant amplitude) in this case. ($18/7\pi = 0{\cdot}818$)

The m.m.f. waveform due to the currents in vector position 3 can be shown, by the usual methods, to be

$$\frac{9}{\pi}x\left(\sin\theta + \frac{1}{3} \times \frac{1}{3}\sin 3\theta + \frac{1}{5}\sin 5\theta + \frac{1}{7}\sin 7\theta + \frac{1}{3} \times \frac{1}{9}\sin 9\theta + \frac{1}{11}\sin 11\theta + \ldots\right) \text{ etc.}$$

Table 2

Particular Cases of Generalized Trapezoidal Waveform

α	β	a_m	Form of half-wave
0	0	$\frac{4F}{\pi m}$	Full rectangle
α	α	$\frac{4F}{\pi m}\cos m\alpha$	Shortened rectangle
0	$\frac{\pi}{2}$	$\frac{8F}{\pi^2 m^2}$	Isosceles triangle
α	$\frac{\pi}{2}$	$\frac{4F}{\pi m^2\left(\frac{\pi}{2} - \alpha\right)}\left[\pm 1 - \sin m\alpha\right]$	Shortened isosceles triangle
0	β	$\frac{4F}{\pi m^2}\frac{\sin m\beta}{\beta}$	Full regular trapezium
α	β	$\frac{4F}{\pi m^2}\frac{\sin m\beta - \sin m\alpha}{\beta - \alpha}$	Shortened regular trapezium

where the amplitude of the resultant wave is $11x/4$. Here the fundamental peak is $36/11\pi$ (resultant amplitude). ($36/11\pi = 1\cdot04$.)

The third symmetrical m.m.f. waveform is given by currents in vector position 4, and its analysis is given by

$$\frac{9}{\pi}x\left(\sin\theta - \frac{1}{5}\sin 5\theta - \frac{1}{7}\sin 7\theta + \frac{1}{11}\sin 11\theta + \ldots\right) \text{ etc.}$$

where the amplitude of the resultant wave is $\sqrt{3}(3x)/2$. Here the fundamental peak is $2\sqrt{3}/\pi$ (resultant amplitude). ($2\sqrt{3}/\pi = 1\cdot10$.)

The unsymmetrical m.m.f. waveform which arises from currents in vector position 2 essentially contains both sine and cosine *odd* terms, but no even harmonics. The usual processes of Fourier analysis show that the amplitude of the mth harmonic is given by

$$\frac{\sqrt{3}}{2}\frac{x}{\pi m}\left(84 - 16\cos\frac{m\pi}{3} - 64\cos\frac{2m\pi}{3}\right)^{1/2}$$

and putting $m = 1, 5, 7, 11$, etc., the value of the terms in the bracket is found always to be $6\sqrt{3}$. When $m = 3, 9, 15$, etc., the value of the terms in the bracket is always 6.

The Fourier analysis of this m.m.f. waveform can thus be written as follows:

$$\frac{9x}{\pi}\left[\sin(\theta - \alpha_1) + \frac{1}{\sqrt{3}} \times \frac{1}{3}\sin(3\theta - \alpha_3)\right.$$
$$+ \frac{1}{5}\sin(5\theta - \alpha_5) + \frac{1}{7}\sin(7\theta - \alpha_7)$$
$$\left.+ \frac{1}{\sqrt{3}} \times \frac{1}{9}\sin(9\theta - \alpha_9) + \frac{1}{11}\sin(11\theta - \alpha_{11}) + \ldots\right] \text{ etc.}$$

where the overall amplitude of the resultant unsymmetrical wave, at its highest point, is $\sqrt{3}/2\left(\frac{7}{2}x\right)$. Hence the fundamental peak is equal to $12(\sqrt{3})/7\pi$ (resultant amplitude). ($12\sqrt{3}/7\pi = 0\cdot945$)

α_1, α_3, etc., are angles which can readily be calculated from the same analysis as that from which the coefficients in the series were derived, but for present purposes these angles are of no significance. What is important is the amplitude of the harmonics; their phase necessarily shifts constantly.

It will be seen that, throughout all these m.m.f. waveforms, the magnitudes of the fundamental component, and of all harmonics which are not of triplen order, remain unchanged; only the third, ninth and other triplen harmonics alter in magnitude throughout each cycle of the supply voltage. In a perfectly symmetrical winding these latter harmonics would, of course, be entirely absent; their presence here is a sign of slight asymmetry, but experimentally this degree of asymmetry has been found to be completely tolerable.

It is, however, fortuitous that all the harmonics except the triplen ones remain constant in magnitude. The relative numbers of turns have been deliberately adjusted to give equality of the fundamental component between the first and extra phases, but this will only give equality of the other harmonics if the coefficients of the various terms in the two harmonic series for the first and extra phases, taken separately, diminish in the same sequence. The series for the first phase, shown in Fig. 5, is as follows

$$\frac{3F_1}{\pi}\left(\sin\theta - \frac{2}{3}\sin 3\theta + \frac{1}{5}\sin 5\theta + \ldots\right)$$

and the series for the extra phases, which have a rectangular waveform, is as follows:

$$\frac{4F_3}{\pi}\left(\sin\theta + \frac{1}{3}\sin 3\theta + \frac{1}{5}\sin 5\theta + \frac{1}{7}\sin 7\theta + \ldots\right)$$

Since $F_3/F_1 = n_3/n_1 \doteq 3/4$, the fundamental and the harmonics of orders 5, 7, 11, 13, etc., have coefficients of equal relative magnitude in both series, and their constant result in the analysis above could have been predicted from this fact.

(10.3) M.M.F. Waveforms in 6-Pole Operation

In Fig. 15 the ampere-conductor loading for 6-pole operation is shown. In the ideal case k would be equal to $(2 + \sqrt{3})$, and

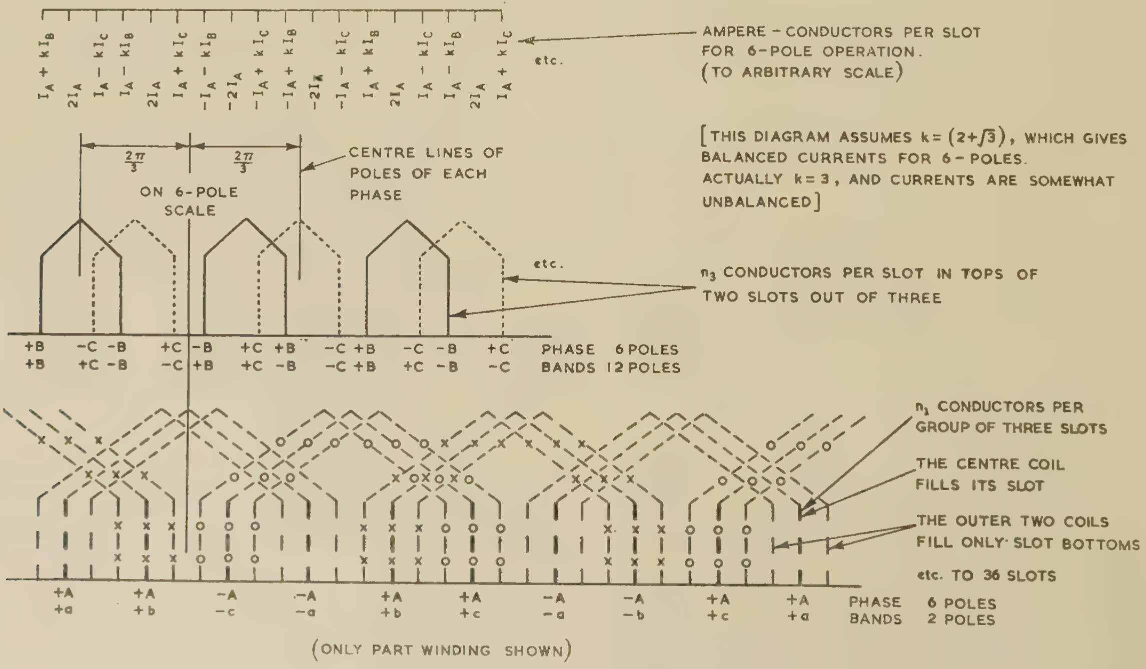

Fig. 15.—Distribution of coil sides and phase bands for 6/2 poles.

the fundamental components of m.m.f. would then be balanced, as shown in Section 5.2. The resultant m.m.f. waveforms, for seven successive vector positions spaced by 30°, are plotted in Fig. 12(*b*) approximately to scale. There was no merit, however, in making full Fourier analyses in this case, because the two harmonic series for the first phase and the extra phases, taken separately, do not diminish in the same manner with rising order of harmonic.

In the actual machine, k was equal to 3 and not $(2 + \sqrt{3})$, because the winding as made correctly for 12 poles was accepted for 6 poles, in spite of being unbalanced, and the currents were also a little unbalanced. Consequently, the waveforms in Fig. 12(*b*) must therefore be taken only as descriptive and approximate, and not as the exact forms for 6-pole operation.

It is, however, possible to calculate the constant fundamental m.m.f. per pole in the ideal case by taking the Fourier analysis of the m.m.f. for a particular current-vector position. The successive ampere-conductor loadings are given in Fig. 15, and putting $i_A = 1$; $i_B = i_C = -\frac{1}{2}$, and $k = (2 + \sqrt{3})$ the first waveform of Fig. 12(*b*) is obtained. From the Fourier analysis of this wave the fundamental amplitude is found to be

$$\frac{3\sqrt{2}}{\pi}(2 + \sqrt{3})$$

ampere-conductors, for the particular case where $\frac{n_1}{4} = 1$.

The m.m.f. expressed in ampere-turns acting on the centre of each pole is therefore

$$\frac{3\sqrt{2}}{\pi}(2 + \sqrt{3})\left[(\sqrt{2})I_{rms}\frac{n_1}{4}\right.$$
$$= \frac{3(2 + \sqrt{3})}{2\pi}n_1 I_{rms}$$
$$= 1\cdot78 n_1 I_{rms}$$

This may be compared with the value $1\cdot01 n_1 I_{rms}$, given in Section 6.2 when the windings are connected for 12-pole operation. Ideally, on changing to 6-pole operation the result would be $2\cdot02 n_1 I_{rms}$. The actual result is therefore 88% of the ideal, this factor representing the reduction of winding factor on changing the pole numbers from 12 to 6, for a given number of conductors in the first phase. There are, of course, rather more conductors than before in the extra phases.

DISCUSSION ON 'AUTOMATIC CIRCUIT RECLOSERS'*

Before the SOUTHERN CENTRE *at* HOVE *2nd November*, *the* RUGBY SUB-CENTRE *at* RUGBY *9th November*, *the* WESTERN SUPPLY GROUP *at* BRISTOL *21st November*, *the* NORTH MIDLAND CENTRE *at* LEEDS *6th December the* NORTH STAFFORDSHIRE SUB-CENTRE *at* STOKE-ON-TRENT *16th December*, 1955, *the* SOUTH-WEST SCOTLAND SUB-CENTRE *at* GLASGOW *4th January*, *the* WESTERN CENTRE *at* CARDIFF *13th February*, *the* MERSEY AND NORTH WALES CENTRE *at* CHESTER *19th March*, *and the* NORTHERN IRELAND CENTRE *at* BELFAST *10th April*, 1956.

Mr. W. E. Gibbs (*at Hove*): What proportion of the networks discussed in Table 1 were of earthed construction? In the South Eastern Area the number of interruptions from lightning during the same period was only 43, although a fault analysis for this Area during the last six months shows over 500 such faults.

Is the steelwork upon which the reclosers are mounted earthed? It may be that it is unearthed in order to obtain as high an impulse level as possible. I note that it should be possible for the reclosers to carry out 100 operations before maintenance is required. How is the impulse level affected following 100 operations? As I see it, it is very necessary for the recloser to have a high impulse level. Installing these reclosers is an expensive business; is the cost likely to be reduced if a 3-phase recloser were constructed in one tank? It seems to me that one has the choice of installing preventive devices such as surge diverters or arc-suppression coils, which would enable lightning surges to be dealt with without interrupting the supply to consumers. These should be effective in many cases, particularly bearing in mind that unearthed construction will be largely used in the future.

Is there likely to be any deterioration in the mechanism when reclosers are installed near the sea and subject to the effects of salt deposit, and is the life of television sets in any way affected by the rapid operation of the recloser?

I take it that the breaking capacity shown in the third column of Table 3 is really a function of the thermal capacity of the operating coil, the circuit-breaker in every respect being a standard piece of equipment.

Mr. R. W. Langley (*at Hove*): The 100 amp recloser is the largest available at the moment; its use is therefore restricted to circuits having a cross-section of $0\cdot04$ or $0\cdot05\,in^2$. The amount of load that can be transmitted on such a line is limited to some 2 MW for 11 kV lines and 1 MW for 6·6 kV lines, and in this Area, which has a fairly high rural load density, such a demand occurs over a comparatively small area. True, the reclosers could be utilized on spurs from the main line, but this introduces economic considerations and it is frequently difficult to justify the expenditure. I feel that the authors have painted too rosy a picture of what is possible in the way of discrimination; Fig. 3(*a*) shows a 50 amp recloser on a line from a main sub-station at 150 MVA and slow-melting fuses on the spurs, and for a $0\cdot05\,in^2$ rural-type h.v. line, the 20 amp fuse on the end is at a point where the fault level has dropped to 8·2 MVA, which would be 10 miles from the source. Surely 10 miles of $0\cdot05\,in^2$ line is very rare in this country. The fault levels which I have calculated from the authors' figures indicate that discrimination would not be certain with the fuses which are shown in series. Discrimination is most important, and since, according to Table 1, the majority of faults are due to lightning, and are in the main 2-phase-to-earth or 3-phase symmetrical short-circuits, especially with B.S. 1320-type construction, a fault current near the upper limit is to be expected. Does Fig. 3 bear any relationship to the authors' trial installations, and how many reclosers of this type have they been able to accommodate?

The suggestion that 'co-ordination of reclosers with sub-station protection can generally be achieved, provided that the number of circuit-breakers in series with the actual source of supply is limited' is rather optimistic: I have had some difficulty in fitting in the recloser with back-up protection, owing to the rather limited time which is available but which in the circumstances is inevitable in the majority of instances.

What experience have the authors had with the new type of expulsion fuse, and has it proved more satisfactory than the liquid type which has been used in the past? I was under the impression that the expulsion fuse had a better short-circuit performance. I do not consider that back-up fuses with reclosers, as indicated in Fig. 1(*c*), are a practical proposition on the majority of lines, since I am doubtful whether discrimination

* PEIRSON, G. F., POLLARD, A. H., and CARE, N.: Paper No. 1717 S, December 1954 (see 102 A, p. 749).

would be possible, bearing in mind the deterioration of fuses which occurs with through fault current.

Mr. C. Freeland (*at Hove*): The narrow current range over which co-ordination with fuses can be obtained appears to set on their application limitations so severe that, when applying such reclosers to a given network, the positions where they are installed might be governed by the limitations of this co-ordination rather than by considerations of where such devices would prove most effective. Have such difficulties been found in the application of automatic reclosers?

The curves illustrating the co-ordination of reclosers and fuses show in the normal manner the characteristics of the latter in the form of clearly defined curves. In practice, however, a considerable tolerance has to be allowed for variation in characteristics, arcing times, etc. Again, fuses of similar construction but different manufacture often show wide differences in their characteristics. All these factors appear to mean further narrowing of the current range to give co-ordination. Has it been found necessary in the practical application to adhere to a single type, as well as size, for a given installation?

Mr. H. E. Cox (*at Rugby*): The success of the recloser depends upon co-ordination between the reclosers and the fuses, and the ease of co-ordination depends upon the current range over which it exists; this range, in turn, depends upon the relative speeds of the recloser and the fuse. There does not seem much prospect of making reclosers with a time to break of less than 0·03 sec, which means that co-ordination on two reclosings can be obtained only up to the current at which the fuse melting time is 0·06 sec. This requirement sets very serious limitations upon the breaking and current capacities of the fuse.

Table 8 shows that co-ordination can be obtained over a useful range, but does not state the voltage to which it applies. Are we to take it that the Table applies to 11 kV, i.e. that the fuse makers have developed a 75 amp fuse that will hold a 2050 amp 11 kV fault for as long as 0·06 sec and then clear it without failure?

I wonder whether the elaborations necessary to give two instantaneous trips followed by two delayed trips and lock-out really gives a worth-while gain over a much simpler recloser giving one instantaneous trip followed by lock closed. May not the added complication cause more interruptions to supply than are prevented by the second instantaneous trip? Each time a recloser is taken out for maintenance there must be an interruption of supply of the whole system beyond the recloser unless live-line maintenance can be achieved.

For 100 average faults the lock-open recloser could carry out 145 break operations and 55 make operations on the fault current, while the lock-closed recloser would effect only 100 break operations and 22 make operations, none of which would be make-break operations. In view of the greater contact erosion on make-break and time-delay operations, it is probable that the lock-closed recloser would handle four times as many faults between overhauls as the lock-open recloser.

Mr. K. A. J. Brooks (*at Rugby*): I think it is generally accepted that, with no overhead earth wire, the fault rate due to lightning is considerably increased, and Table 1 indicates that 46% of the faults were due to lightning. My experiences of 132 kV transmission faults leads me to suspect that the causes listed as 'unknown' in the Table could be added to this figure with negligible error, bringing the percentage to 66. These figures would seem to favour the adoption of an earthed system utilizing surge diverters, which has been developed to a point where it can be used successfully to discriminate with a fuse. This system might offer a saving in the capital cost and still give continuity of supply under transient fault conditions.

In my experience, the most common form of accident to low-voltage distribution lines has been due to farm-workers entangling machinery, particularly hay balers, in the overhead wires. The high-speed automatic recloser, with its repeated closing sequence, might therefore offer some increase of danger in these particular circumstances.

The authors make out a case for the use of the recloser in Table 2 by indicating the length of time required to replace fuses. As they have said, however, it is possible to achieve a considerable saving in both time and cost by suitable grouping of transformer supplies under the control of a single set of fuses. This arrangement has been in operation for some time, and I should like the authors' views on the extent to which it has reduced the time required for replacement.

Table 3 seems to imply an accepted maximum fault potential of 50 MVA. With a rapidly expanding and integrated network such as we have in this country, is this figure high enough for general application? Furthermore, I presume that any switchgear offered for such an application will ultimately have to possess an A.S.T.A. certificate. In order to obtain such a certificate, at say 50, 75 and 100 MVA, will not the reclosure mechanism have to be more robust than that indicated in the paper, thus increasing its ultimate cost?

The authors stress the need for co-ordination with fuses and for a change in the generally accepted characteristics of such fuses at present in use, so as to permit them to be rather slower in action and to pass fault current without detriment. Operational results obtained by this combination will be awaited with interest. My experience with oil circuit-breakers suggests that the maintenance of this device will be frequent and therefore relatively expensive. This would seem to indicate that here is a sphere in which the air circuit-breaker might be supreme.

Mr. W. Hill (*at Bristol*): I should like to raise the question of rupturing capacity. We now have primary substations feeding into the 11 kV network in rural territories, and the fault power is 150 MVA; it seems a pity that we cannot protect the first section of line, but have to go out approximately two miles before we can use a recloser. I hope that something can be done towards getting a slightly higher fault capacity.

Mr. A. H. McQueen (*at Bristol*): The late H. W. Clothier pioneered the automatic reclosing circuit-breaker 25–30 years ago. It had six reclosers stored up before lock-out and had a fast-acting device which caused it to trip and lock out on a sustained fault. A great advantage was that it had a high insulation value and consequently there have been very few breakdowns. Many of these circuit-breakers are in service to-day, their main disadvantages being weight and rather high cost.

Fuses, no matter how well designed or constructed, are subject to deterioration by either prolonged use or intermittent overloading when a recloser operates. Consequently the high degree of continuity of supply which is now being demanded in rural areas cannot in practice be given, although theoretically it would appear to be so. I consider that the best arrangement for a rural network is to use subsidiary circuit sectionalizers and a recloser on the main circuit.

What are the characteristics of the relay curve shown in Fig. 4? With a time multiplier of 0·3 and a current setting of 150% on a 300/5 amp current transformer, the curve appears to show operation at 1·4 sec at ten times full load, whereas a 3 sec inverse-definite-minimum-time-limit relay would operate at 0·9 sec. The relay curve appears to be high in relation to the main portion of the system.

Mr. A. G. Milne (*at Bristol*): The present cost of approximately £380 for the recloser is too high a price to pay for reducing—not eliminating—only the transient circuit interruptions, which are not unduly high. The ratio is further diminished when account

is taken of the fact that in this Area roughly one-third of the overhead system is protected by arc-suppression coils, and this, of course, precludes the employment of reclosers. Some reduction could be achieved by other means which are less costly, e.g. conventional oil circuit-breakers with automatic-reclose devices in conjunction with repeater fuses and the conventional automatic-reclose circuit-breaker (which is only half the price). Although the same high speeds of operation are not attainable, they could be accelerated, and in either case the supply could be restored in a matter of seconds. The rural consumer should find this less onerous than paying more for his supply.

One of the operational difficulties with the high-speed automatic recloser is the conflicting requirement of adjusting the open-circuit time so that it is neither too short (say 0·25 sec) to allow for the dispersal of the ionized path nor so long (say 1–2 sec) as to cause tripping of no-voltage releases on rotating machines and excessive deterioration of fuses.

Mr. A. J. Coveney (*at Leeds*): The authors' claim that 80% of the outages on rural networks could be avoided by the use of reclosers would appear to make the installation of these units a necessity. A proviso, however, is made that their satisfactory operation depends on the correct co-ordination with fuses, and slow-melting fuses must be adopted in a large number of cases. The economics must therefore be considered, for it does not necessarily mean the cost of the installation of these units only, but also the purchase and re-equipping of lines with slow-melting fuses, new designs of which the authors advise us are now available, together with the alternative of the installation of the sectionalizer unit. The tendency, therefore, to displace high-speed fuses by the slow-melting type is one which I feel should be deprecated, because the slower clearance times under fault conditions by the latter fuse would provide more system shock and allow fault currents to reach higher values. It would therefore appear that, if the operating staff want the advantages of a reduced number of shut-downs caused by lightning and other transients, they must suffer the cost of installing and the disadvantages of increased fault-current disturbances arising from the replacing of fast-acting fuses by slow-acting ones.

In regard to earth-leakage protection, the fact that the series-current operating coils are limited to a minimum trip value of twice full load would in some cases give a very high value for earth-fault clearances, and I feel that switchgear designers should provide, in addition to the automatic closing features, a unit which can give sensitive earth protection of low settings. In this respect it would appear better to provide a separate closing means, series over-current tripping coils large enough to withstand the full short-circuit through currents, and a shunt tripping coil which could be used for fault currents below normal full load. There seems to be no reason why current transformers could not be included for this purpose and built into the recloser bushings. With the present arrangement it is necessary to select the correct size of current coils and to ensure that these are in accordance with the fault levels at the various points where the reclosers are installed.

Again, from the economic aspect, it might be better from a manufacturing point of view to have a standard 3-pole unit, omitting one phase for application to the British type of single-phase lines, using phase-to-phase construction. If a single-pole recloser is used on this type of line, the unprotected conductor will become dangerous under earth-fault conditions, so that two single-pole units are obviously necessary.

The adoption of the American units on British networks, followed by British-manufactured units, has obviously provided an excellent means of dealing with transient faults quickly, but it is questionable whether these units still meet the many issues which confront the British type of rural distribution supply.

Mr. P. Finch (*at Stoke-on-Trent*): Difficulty might be experienced in grading the time-delay trip of the circuit recloser with the earth-fault protection of the back-up circuit-breaker. Fig. 9 shows the discrimination to be obtained between the recloser and a circuit-breaker having an over-current-relay setting of 150%, a time multiplier of 0·3 and a current-transformer ratio of 300/5. In practice, the majority of transients are earth faults, and the co-ordination between the recloser and the earth-fault relay must therefore be carefully considered. Fig. 18 shows that with a fault current of 415 amp the recloser is held closed for 3·6 sec, during which time the back-up earth-fault protection is not expected to operate. For correct discrimination, therefore, the earth-fault relay must not operate in less than 4 sec, and this requires, with 300/5 current transformers, a plug setting of 80% and a time multiplier of 0·33. On many distribution networks throughout the country it is not possible to permit such a high earth-fault setting, especially where distribution substations equipped with automatic circuit-breakers are supplied by means of a closed ring. Is the back-break characteristic of the time-delay trip really desirable, and, if not, are any means available for improving its shape?

Mr. S. H. Money (*at Glasgow*): The cause of fuse rupture during lightning storms has always been a source of controversy, and I should like to know whether it occurs on systems where reclosers are used. If the fuses do not rupture, is this due to the use of slow-melting fuses or to the high-speed operation of the reclosers?

It is a pity that the reclosers could not be fitted with earth-leakage protection, for in the south-west of Scotland about 60% of the total faults are earth faults. The earth-fault current is often less than the load current, so that the circuit-breaker will not operate; indeed, a broken conductor lying on the ground will often pass only 70 amp, yet Fig. 4 gives a minimum tripping current of 500 amp at the main substation. Have the authors not found it necessary to fit earth-leakage protection to cater for broken-conductor conditions?

In Table 6, the number of faults recorded per mile of line seems unusually high; the fault level appears to be 125 per annum per 100 miles of line, whereas in this Area the average is about 27.

The cheapest form of lightning arrester is probably the rod-gap, and it would appear that, with high speed circuit-breakers, rod-gaps could be used to protect the apparatus at all earthed points. It would also seem possible to reduce the spacing on these dual rod-gaps to a minimum, say 1 in.

Mr. P. M. Prior (*at Cardiff*): With the increasing use of live-line working, should provision be made to enable the automatic circuit reclosers to be made non-reclosing, to increase safety while work is being carried out on sections of system covered by the reclosers? The point is also relevant when dead-line working is in use: when the system is recommissioned after maintenance, should not any automatic reclosing circuit-breaker be made non-reclosing?

Mr. R. A. Woods (*at Cardiff*): On lines of earthed construction there would appear to be some advantage in having co-ordinating gaps on the bushings, particularly on the outgoing side of the recloser.

I should like the authors' views on the relative merits of earthing or not earthing the tank of the recloser when erected on lines of unearthed construction.

Mr. J. S. Lombard (*at Cardiff*): In the early days of rural development fuse protection, mostly of low ratings, was used extensively for the control of new lines and substations, with the result that the passage of a single lightning storm often left the district engineer with a score of fuses to renew and a long trip around the system to prove the supply at many substations. If he neglected to do this, it was not unusual for a consumer to inquire some 24 hours later when his supply would be restored.

Storms on several successive days are not unusual, and this could easily denude him of fuse replacements.

In time, many fuses were replaced by solid links and weight-operated automatic reclosers were used to control groups of lines; a very large proportion of the faults were transient and the circuit-breaker restored the supply swiftly. Sectionalizing of the network had to be carried out after a sustained fault and many consumers were disconnected for more or less long periods depending on the network layout, although the total number of consumer-hours lost in this method was far less than with indiscriminative fusing. The combination of the recloser and slow-melting fuse now available is a refinement which gives the benefit of both automatic reclosing after transient faults and automatic clearance of faulty spurs, and I hope there will shortly be a number of these units in commission in South Wales.

The rapid clearance of faults which is a feature of this apparatus has the additional advantage of reducing damage caused by fault currents, and we may well find in practice that the percentage of faults now labelled as transient will tend to increase as damage is minimized.

Mr. A. C. Davies (*at Cardiff*): The lack of fairly sensitive earth-fault monitoring in the recloser mechanism poses problems of application, both in obtaining correct operation and designing economic schemes. With the exception of fallen-conductor faults, the earth-fault currents experienced on modern lines can be partly controlled by earth mats at specific poles carrying transformers, switches and certain cradle guards. The back-up circuit-breaker will have sensitivity related to this prospective current, and if reasonably fast operating times are required at current levels of the order of 200% of the 50 or 100 amp recloser ratings, it is not easy to ensure discrimination between the recloser and the circuit-breaker. The problem is made more easily soluble by increasing the earth-fault current, i.e. by increased expenditure on earth mats, but since a typical line section controlled by one recloser would have a large number of individual earth mats, the extra expenditure may be detrimental to the economics of the scheme.

Mr. W. H. Thompson (*at Chester*): The first necessity in the event of a fault is that the recloser shall trip and reclose at high speed; this will clear true transient faults. Secondly, there should be a pause of a few seconds to allow second-order faults to develop, after which the recloser should again trip and reclose; if the fault persists, a trip and lock-out should follow immediately. There seems nothing gained by further trip-close operations.

Circuit-breaker testing to B.S. 116 is B-3MB–3MB. The authors suggest another make-break duty, making four break duties in all. They later state that one recloser performed 209 duties in 24 hours, i.e. 2 630 amp (50 MVA basis) interrupted every $6\frac{3}{4}$ min, without contact or oil change. This is hardly continuity of supply, and it makes the proposed 4-duty-cycle test inadequate.

The minimum open-circuit time is given as 0·25 sec, or $12\frac{1}{2}$ cycles. While such high-speed and single-phase reclosing is necessary on very high-voltage long-distance transmission, it is not needed on 11 kV networks. Therefore, the complication of high-speed single-phase features in this recloser seems hardly justifiable.

The remarks on the weight-operated circuit-breaker are incorrect. This unit can have a minimum dead time of about 5 sec and the reclosure times can be varied as required.

The new device is undoubtedly a good achievement and has great application, but it is equally true that the experience gained with the weight-operated circuit-breaker, with its higher breaking capacity and current rating and its relative simplicity, shows this to be the correct and more economical choice for many applications.

Mr. H. G. Jones (*at Chester*): The film showing a recloser clearing a flashover on an 11 kV insulator is obviously a 'fake'. It must be a creepover, not a true flashover, and there is much difference between the two. For a flashover the applied voltage would peak at about 120 kV and there would be nothing left of the recloser, since its impulse withstand voltage is given at 95 kV. The illustration might be taken (though not intended) to show that the recloser is capable of dealing with lightning flashovers and follow current. It cannot possibly do this, and in areas subject to such lightning effects it would be anathema. Again, if a conductor fell to earth in a location of high earth resistivity, such as many parts of North Wales, the recloser would not clear. Moreover, its presence would have caused the removal of the last line of defence, albeit a puny one. This is why we tend to favour the Petersen coil for North Wales.

The ideas so ably advocated provide advantages greatly needed. They also, unwittingly, emphasize the ineptitude of current-operated earth-leakage protection. Perhaps the urge to gain the advantages without the converse might give impetus towards the extension of voltage-operated earth-leakage protection beyond the medium-voltage regime.

Mr. E. G. Davies (*at Chester*): The authors mention that reclosure after 1 sec will permit continuity of supply without the no-voltage release operating. Since it will normally have operated in approximately 40 millisec, are they referring to delayed no-voltage release?

Mr. W. Szwander (*at Belfast*): While the basic principle of applying automatic reclosers is no doubt sound and appears most attractive, it is to be regretted that the paper does not give any information on the economics of this application. Obviously in any given distribution system it must first be decided to what extent additional expenditure for improving the supply continuity is justifiable. If such is the case, the means best suited to the purpose must be selected from the various possible solutions; e.g. improving the effectiveness of the fuse-replacement service, improving the mechanical and electrical characteristics of the distribution equipment with a view to reducing the fault incidence, the use of automatic circuit reclosers and the application of arc-suppression coils. The latter, which constitute standard equipment in the majority of rural distribution networks on the Continent and give most satisfactory service, obviously do not represent a perfect solution of all the problems involved; the automatic reclosers, however, are also far from being an ideal in every respect, e.g. consider cost, mechanical complication, need of maintenance, limitations of co-ordination. There is much unjustified prejudice against the use of arc-suppression coils in this country, and only a fair practical trial of them, and of automatic reclosers, in comparable distribution systems, can give an acceptable solution to the problem.

Before rushing to imitate American practice, we should remember, not only that most of their systems cover areas with lower population and load densities than ours, but also that American practice was traditionally associated with the principle of solid earthing of the neutral, and that the phase/neutral single-phase distribution widely used in the United States rules out the possibility of applying arc-suppression coils, leaving automatic reclosers as the only alternative.

Mr. E. L. Tapson also contributed to the discussion at Bristol, **Mr. E. B. May** to the discussion at Cardiff, and **Mr. S. T. Wellby** to the discussion at Chester.

Messrs. G. F. Peirson, A. H. Pollard and **N. Care** (*in reply*): In reply to Mr. Gibbs, the statistics submitted in the paper related to a mixed high-voltage system having various types of earthed construction and also a large proportion of unearthed construction. The route mileage of the unearthed construction was about 50% of the total, as shown in the following Table:

H.V. Rural Lines in Midlands Board Area

	Over-running earth wire	Under-running earth wire	Individually earthed poles	Unearthed construction
Route miles of line	203	911	335	1 404
Faults per 100 route miles per annum	2·0	6·1	6·9	4·3

Reference should also be made to our comments on the points raised by Mr. White at the London meeting.

We are surprised at the small number of interruptions due to lightning, unless this is intended to represent failures of plant due to lightning. It is the general experience throughout the country that transient interruptions due to lightning are between 70 and 80% of the total number.

We agree with Mr. Gibbs that it is advantageous for reclosers to have a high impulse level, and if the steelwork of the recloser is not earthed, as in B.S. 1320 lines, it considerably increases the impulse level of the device to earth.

Tests taken so far have demonstrated that the impulse level of the recloser is not materially affected by the suggested 100 operations prior to maintenance.

In connection with the use of surge diverters instead of reclosers we would refer Mr. Gibbs to the general practice in the United States, where, in spite of the multiplicity of surge diverters fitted to all applications, reclosers are being installed in increasing numbers. Some of the disadvantages associated with the use of arc-suppression coils are given in Mr. K. M. Jones's contribution to the London discussion.

The construction of the mechanism is such that any deterioration due to corrosion which might be caused by the proximity of the site to the sea will not affect the operation of the device.

The provision of a 3-phase recloser in one tank has obvious disadvantages in that a much heavier unit is provided, making handling more difficult, and single-phase lock-out would not be easily achieved. In addition, single-phase tripping would be very difficult to obtain, and 3-phase tripping and reclosing would have a much more serious effect upon low-voltage supplies to motor loads.

In reply to Mr. Langley, the figures produced in other parts of the country indicate that the 100 amp recloser should prove adequate for main lines providing supplies to rural areas. Examples in Cumberland and North Wales show that for a loading of 2 MVA approximately 500 farms could be dealt with, which, with average spacing of such premises, would mean that about 200 miles of line could be protected by one recloser.

It has been found that the slow-melting fuses which have been tested in conjunction with reclosers are very consistent in their characteristics, and there should be no difficulty with discrimination on typical systems having circuits as shown in Fig. 3. This Figure merely shows the principle of utilizing reclosers in the main lines, and this is the method which has been adopted in the trial installations on reclosers on the M.E.B. systems.

We agree with Mr. Langley that some difficulty will be experienced in fitting the back-up fuses shown in Fig. 1(*c*), and this is one of the reasons why the lock-closed arrangement was not adopted.

With reference to Mr. Freeland's comments, the range of co-ordination given by the British recloser is much wider than that given by the majority of those manufactured in other countries, and the latter reclosers are being successfully applied to all forms of rural systems.

It should be pointed out that a factor has been included in the current/time characteristics for fuses to cover for tolerances, arcing times, etc., as shown in Fig. 2 of the paper. In practice, it has not been found necessary to restrict the type of fuse used to any one particular design or manufacture.

We thank Mr. Cox for his comments, but feel that the use of two instantaneous trip operations has been justified in the paper, and since this feature can be very easily provided with the mechanism designed adopted, it has been included without, in our opinion, seriously reducing the range of co-ordination.

To Mr. Brooks's comments we would add that even when surge diverters are installed at all points considerable trouble is experienced due to the rupture of fuses on transient faults.

It should be pointed out that the policy of group fusing supply transformers has been adopted in the Midlands for some considerable time. Under these conditions, transformers are grouped on spur lines, and provided that there are no more than six, one set of fuses at the spur connection has been adopted. A recloser installed in the main line may protect a considerable number of such spur connections, and the operation of fuses under transient conditions at these points is thus avoided. In addition, the presence of a recloser prevents fuse deterioration due to the high-speed trip operation of the recloser.

The 50 MVA breaking capacity given in the paper is covered by an A.S.T.A. certificate.

It is not anticipated that maintenance will have to be at more frequent intervals than one year, and after experience has been obtained this interval may well be lengthened.

We feel that Mr. Brooks will find some difficulty in obtaining an air circuit-breaker to operate under the conditions and in the locations where reclosers are normally placed.

In reply to Mr. Hill we feel that, in practice, the interrupting capacity of the recloser will not prove any hardship. Where cases of high fault level have to be met there would be no objection to including a similar reclosing duty on circuit-breakers situated at the primary substation concerned.

In reply to Mr. McQueen, fuse protection of rural lines has been reasonably successful from the aspect of false operation of the fuses, and with the introduction of the more robust slow-melting fuse we expect even better results.

We cannot agree with Mr. McQueen, who appears to have overlooked the current setting of 150%; ten times full load therefore represents only 6·67 times the setting and so gives a longer tripping time than the 0·9 sec stated.

The relay curve shown is substantially correct for a B.S. relay.

With reference to Mr. Milne's comments, with conventional automatic reclosing circuit-breakers a sufficiently high speed of operation to protect fuses is not normally obtainable. Consequently, the arrangement will not give the discrimination desired, and the feature whereby automatic sectionalizing of the network is obtained under permanent fault conditions is lost. Repeater fuses provide for restoration of supplies under transient conditions only, but are quite inadequate to meet conditions during typical thunderstorms, when many flashovers on one section might occur in succession.

In reply to Mr. Coveney, with the automatic-circuit-recloser-protected line there has been a reduction of permanent faults, because the operation of the device is so rapid that transient faults do not damage the line or its insulation.

Where a permanent fault has to be cleared by a fuse the possible increasing damage between the conventional and slow-melting fuse can be ignored. It should be pointed out that to obtain slow-melting features it is necessary only for the element in the fuses to be changed. This is a relatively easy matter and can, if required, be left until fuse elements are being replaced after faults have arisen. There is generally no need to change the fuse-holder or its mounting.

A device such as Mr. Coveney suggests would be expensive,

and for this reason is unlikely to be acceptable for rural-line application although the features enumerated are desirable.

In reply to Mr. Finch and Mr. A. C. Davies, there are a number of conflicting considerations applicable to every system, and for each application these must receive detailed consideration. We would point out to Mr. Finch that the characteristics of the recloser are easily adjustable.

Where it is possible, without interfering with the discrimination obtained with the back-up supply circuit-breakers, the earth-fault time delay should be set to the maximum; where the earth-fault protection imposes a limitation, it is possible to supply a recloser with a reduced time delay, but this will limit the range of co-ordination. It must be remembered, however, that once a recloser has been included in the network it is necessary for the back-up protection to protect only the main line and the portion of the line between the primary substation and the recloser. Under these conditions adequate discrimination should be possible, since many of the low earth-fault settings which have previously been necessary on rural systems can now be catered for in the recloser itself.

We agree with Mr. Money that fuse rupturing has occurred under lightning conditions. We feel, however, that the introduction of a recloser makes this rupture more unlikely, since at the time of the lightning stroke and the follow-up power arc, the fault is interrupted by the recloser itself. Where a persistent fault has occurred, the fuse merely interrupts the fault current in accordance with its capacity and no rupture should occur.

While we agree that low earth-fault current can cause difficulty, it must always be remembered that the recloser will trip at a lower fault setting than the circuit-breaker at the main substation. We agree that the number of operations of the reclosers shown in Table 6 is high compared with average conditions. This is no doubt due to the fact that localities were selected for the test conditions where lightning interruptions were known to be prevalent. In addition, a large number of operations occurred during the coastal storms of February, 1953, when heavy salt deposits accumulated on a large number of rural lines in the northern portion of the Midlands Area.

We agree that the inclusion of a recloser opens up a new field for the use of rod-gaps, and so provides a very cheap means of restricting excessive over-voltages.

Mr. Prior will note from the paper that the standard unit is arranged so that if it is manually closed on to a fault the recloser will open once to clear the fault and lock out. While we agree that this does not prevent reclosing should a fault occur during live-line working, it would be very complicated indeed to provide for this feature.

In reply to Mr. Woods, double horn-gaps are fitted to each side of the recloser. We believe that it is better not to earth the tanks of the recloser; this increases the impulse level to earth.

We would refer Mr. Thompson to the London discussion for our comments on the recloser duty and the short-circuit testing conditions. Our principal criticism of the weight-operated circuit-breaker is that the tripping time cannot be varied over the reclosure cycle; thus it is not possible to use a weight-operated circuit-breaker to provide for both the restoration of supply, after transient faults, and the automatic sectionalization of the network under permanent fault conditions.

Under the condition of 120 kV peak voltage, specified by Mr. H. G. Jones, the recloser would not suffer any damage.

A flashover on the recloser itself would be over the horn-gaps. Should it occur on the line side of the recloser, it would be cleared by the recloser itself, while on the supply side it would be cleared by the substation circuit-breaker.

The film was intended to show the variation in the magnitude of power follow-up arcs resulting from high-voltage spillovers on line insulation. With the high-speed recloser in series the duration of the power arc is so reduced that damage to insulation is prevented. It is, of course, admitted that where direct lightning strokes occur, damage from the lightning stroke itself may be unavoidable.

We would point out to Mr. E. G. Davies that the hold-up of no-voltage releases is due to the fact that the loss of one phase on a high-voltage supply, due to the opening of a recloser, causes a relatively small voltage reduction on the equivalent phase of the medium-voltage network.

Whilst we agree with Mr. Szwander that the continuity of supply must have an economic advantage, we believe that the cost of installing reclosers can be fully justified purely against the saving in expenditure which will result from the cost of fuse replacement. Other methods of improving continuity of supply might be even more expensive, and we think that we should look upon the recloser as the means whereby cheap and effective fuse protection can be adopted in place of the more expensive sectionalization of networks by the use of circuit-breakers.

With regard to the use of Peterson-coil earthing, we would refer Mr. Szwander to the comments made by Mr. K. M. Jones in the London discussion.

Mr. Lombard's comments indicate the advantage of the use of reclosers from the operating engineers' aspect. The experience obtained on the use of reclosers in the Midlands fully justifies these views, and in addition indicates that continuity of supply is improved, running costs are reduced and the capital expenditure involved is fully met by the resultant annual savings.

DISCUSSION ON 'ELECTRICAL ENERGY FROM THE WIND'*

Before the SOUTH-EAST SCOTLAND SUB-CENTRE *at* EDINBURGH *6th December*, 1955, *the* MERSEY AND NORTH WALES CENTRE *at* LIVERPOOL *23rd January*, *the* SOUTH-WESTERN SUB-CENTRE *at* TORQUAY *26th January*, *and the* WESTERN SUPPLY GROUP *at* BRISTOL *20th February*, 1956.

Mr. J. Venters (*at Edinburgh*): Small-scale wind-power sets may be regarded as covering the range 0–2 kW. They are economic for lighting isolated premises, and there has been a large demand for them, but it is now rapidly falling off. The need is disappearing with the spread of the distribution networks of the electricity supply authorities. Wind-power sets rated between 2 and 100 kW may be regarded as medium-scale sets, and it so happens, that, in Scotland, there are no isolated communities for which they would be economic. They can be supplied by Diesel power, and occasionally a small hydro-electric scheme may be practicable. Wind-power schemes of this size are uneconomic on account of the high cost of the battery. By comparison, large-scale windmills of 100 kW capacity and over could become generating units of importance and produce significant quantities of energy. They can justify every effort devoted to their development. There is no uncertainty about the vast quantity of energy in the wind. Given the machines, enough energy could be extracted in Scotland to meet all demands for light, heat and power, and there would be no noticeable diminution in the windiness of the weather.

* GOLDING, E. W.: Paper No. 1727 S, November, 1954 (see 102 A, p. 677).

Fig. 1 is an excellent diagram for studying the principal design factors. It shows that, even on a good site, a windmill will be shut down for a total of three months in every year. For half the remaining time there is more energy than the generator can absorb, and during these periods it would be advantageous to have a device permitting substantial speed variation with changes in wind speed. It would improve governing and steady the output, since governing is difficult at high wind speeds. Where an induction generator is used, a suitable device would be extra rotor resistances automatically introduced into the circuit when the rated output of the generator was exceeded. During the remaining period the generator will be only partially loaded, and every effort should be made in the design to increase the output of saleable units. This can be done by arranging that the aerodynamic performance of the sails is at its maximum at wind velocities between 17 and 30 m.p.h., and by reducing losses in the auxiliary motors and pumps and in the resistors, lubricating oil heaters, etc.

The velocity/duration curve in Fig. 1 is based on mean hourly wind speeds, which has the effect of minimizing the influence of high winds and reducing the estimated power output. The ideal curve is based on instantaneous wind velocities and lies appreciably to the right of the curve shown in the Figure. Thus, in order to avoid running the machine with gusts exceeding 60 m.p.h. or more, when governing becomes difficult, it will be necessary to initiate the shut-down signal when the mean hourly wind speed is only about 45–50 m.p.h. There will therefore be a loss of output due to high winds much greater than that shown in the Figure, but, on the other hand, there will also be a substantial increase in the energy generated when the machine is running over what is indicated by the diagram.

It seems that, if wind power were used on a large scale, the rated wind velocity of the windmills would require to be 30 m.p.h. or less in order to avoid making additional demands on hydro-electric storage. Since wind-generated electricity cannot be stored economically, it must be used when available. By comparison, hydro-electric power with storage can be produced as required, but as running costs are relatively negligible, it is invariably used to the full extent of the water available. Hydro-electric power without storage, i.e. from run-of-river stations, must also be used when available, and therefore has the same characteristics as wind power, except that the seasonal fluctuations are much greater. A relatively small addition of thermal power to a predominantly hydro-electric system has the effect of converting a large volume of non-firm hydro-electric power to firm power, and it is thus advantageous to operate hydro-electric *and* thermal stations together in one system under a single control. Therefore, when wind power is introduced into a mixed hydro-electric and thermal system, the effect will be to reduce the consumption of fuel in the thermal stations. The wind-power units are thus worth the price of the fuel they have saved, and this saving will be spread over all the thermal stations in use, although it will tend to concentrate on the less efficient stations where fuel costs are high and which the control engineers endeavour to run as little as possible. An exact calculation of the saving in fuel cost is probably impracticable, and it is suggested, therefore, that the wind-power units should be evaluated by equating them to the average cost per kilowatt-hour sent out of the fuel consumed in the thermal stations. This figure can be obtained from the annual returns, by dividing the total cost of the fuel burned by the number of kilowatt-hours sent out from the thermal stations. It will be appreciated that this figure will be on the low side, and, in practice, the true value of the wind-power units to the system will be higher than it indicates.

There is ample wind power in Scotland, and thus more than adequate justification for making use of it. The day is now due when a start can be made in gaining operational experience, and it is hoped that it will not be long delayed.

Mr. J. Griffin (*at Edinburgh*): I should like to have more details about the purely electrical aspects of the generators and their control gear, although it is, of course, agreed that the complete equipment must be considered as a unit, and the choice of generator depends, to some extent, on the choice of propeller or turbine. In particular, more information on the relative merits of synchronous and induction generators would be helpful to industry; so far as speed control is concerned, there can be little difference, since both types are, for all practical purposes, constant-speed machines, and they are almost equally difficult to connect to the line (unless induction-motor starting is used). The induction generator can be made suitable for variable speed, but only by substituting for the simplicity of the squirrel-cage rotor the complication of a wound rotor and the associated resistors; the resistor loss may, in the circumstances, be acceptable. The a.c. commutator 'motor' alternative is superficially attractive as a variable-speed generator, but the additional control gear and the maintenance required for both types might be important considerations on isolated sites. I understand that the generator erected at St. Albans is, in fact, a synchronous induction motor, and I would like to have the author's views on this choice. The flexibility given to both the electrical and mechanical sides by the Andreau principle seems an attractive advantage.

Mr. W. R. Gatliff (*at Liverpool*): The author has shown the considerable potential that exists, even in this country, for wind generation. We now have two quite sizeable plants which generate 100 kW each when connected to the Grid system. One of these is an induction generator, and the other, at St. Albans, is a synchronous generator. The problems that have been encountered seem to have been largely on the mechanical side, whereas the electrical side has been fairly straightforward.

I would like the author's comments on the use of wind generators on their own, apart from a Grid supply, when problems arise on the electrical control aspects. Up to the present, wind generators, when operated on their own, have been generally below 10 kW, have generated direct current, and have been used with a battery. It is then fairly easy to control the voltage, and speed variations do not greatly matter.

However, there seems to be a demand for an a.c. generator working in isolation, and it is then necessary to control the frequency to within fairly close limits. Is there some means of controlling the speed other than the mechanical complication of feathering the propeller?

Is there any future for the Andreau principle of construction using an air turbine? If this is to be used without a Grid supply, it will be necessary to have a speed control for the propeller as well as a separate speed control for the air turbine and alternator.

Mr. W. Holttum (*at Liverpool*): Since there must be a limit to the wind speed, above which any further power is wasted, would it be possible to raise this limit by having more than one generator on the shaft, so that, when the first had developed its maximum power, another would cut in and so use the additional power available beyond the limit of wind speed for the first generator? The possible benefit would doubtless depend upon the ratio of the cost of the generator to that of the whole unit, and I would like to know this ratio.

Mr. G. F. L. Dixon (*at Liverpool*): I notice that both synchronous generators and induction generators have been used in schemes where the aero-generator feeds energy into an existing distribution network. I would have thought that the induction generator was the obvious choice in most cases. These are inherently simple and robust, they are self-exciting and self-

regulating, and they need no synchronizing gear. Would the author discuss the grounds on which a particular type of generator is chosen for a given scheme?

Mr. J. Collins (*at Liverpool*): The author has really indicated two main reasons for using wind power: one as an alternative source of energy in order to save fuel, and the other to have a source of energy in areas where fuel for other types of energy is difficult to obtain or transport.

The author and his co-workers have covered a very wide field, but what is the next move? Is it perhaps to concentrate on a rather narrow field? If the author had, say, a quarter of a million pounds sterling made available to carry out the next step, what would he suggest to give the best results? Would he concentrate on small units in, say, some of the islands off the coast of Scotland and obtain operational experience there, or would he continue with development along broad lines to get the maximum information on the widest scale?

British manufacturers of power plant have gained a great deal in the past from the experience of operators in this country, and it could well be that a scheme of small self-contained plants in the Islands might provide a background of information which would be useful to industry in developing business oversea against this home experience.

Mr. U. G. Knight (*at Liverpool*): The author mentions that, according to E.R.A. records, a spell of calm weather often covers a large area, and hence suggests that, even on a system containing a number of wind-driven generators, all the machines would sometimes be out of operation at the same time. For large-scale utilization, the generators would therefore have the function of fuel savers.

It appears that one of the principal design aims should be to ensure that a prospective wind-driven machine to be connected to a supply network should produce the maximum energy per year. As the power output is proportional to the cube of the rated wind speed, I estimate that the energy output for the machine in Table 1 would rise continuously if V_p were increased from 25 to 45 m.p.h. Again, in Fig. 2, except for annual mean wind speeds of about 14 m.p.h. or below, the energy output would increase steadily if V_p were altered from 20 to 25–30 m.p.h.

It seems, therefore, that there might be advantages from the energy production point of view in designing large-scale windmills with rated wind speeds of 40 or 45 m.p.h. for use on the windier sites.

Dr. N. G. Calvert (*at Liverpool*): One of the early applications of the windmill to electrical generation was on the polar ship *Fram*. In 1893 this vessel was allowed to become locked in the polar ice, and throughout the long arctic night her crew depended on a windmill for electric light. Judging by Nansen's enthusiastic writings, the method was most successful.

Most of the machines illustrated have three blades. Two-bladed machines can give trouble when slewing owing to changes in the moment of inertia about a vertical axis as the blades move from a horizontal to a vertical position. These changes (together with constant angular momentum) can give rise to violent angular accelerations.

Very small domestic machines are often not placed in ideal situations, and marginal wind speeds (5–8 m.p.h.) can become important. Cameron Brown in 1933 suggested that about 1 500 hours per year might be a representative duration for such winds. At these low wind speeds efficiency is important, since it represents the difference between a trickle charge and no charge at all. Difficulty can arise with shunt machines at these marginal wind speeds. The mill speed builds up until the set cuts in, the load then pulls the speed down until the set cuts out, and so a state of vibration supervenes; a permanent-magnet alternator charging through a rectifier seems to offer a solution. By avoiding field loss the efficiency could be high and there would be a gradual, not an abrupt, building up of the load.

Mr. W. F. Smith (*at Torquay*): In Section 5, the author deals with economics and indicates the capital costs for wind-driven generators of various capacities, the anticipated cost for large plants being stated as £55 per kilowatt compared with £200 per kilowatt for small plants. I have some difficulty in reconciling this with a statement made some years ago by Schneider in Chicago. He held the view that certain principles applying to other prime movers are not applicable to windmills, in that in a given line of windmills all linear dimensions are in proportion to the wheel diameter D. The area of the wheel and the power of the mill increase as D^2, but the material weight and cost increase as D^3. He contended that this has the abnormal effect of making the cost of power produced by a large mill greater than that for a smaller mill.

It would thus seem advantageous to employ large numbers of comparatively small mills rather than embark on the production of equipment designed for outputs of 2 or 3 MW each. However, I can foresee considerable difficulty. Those associated with the design and construction of power lines over open country are well aware of the strong opposition on amenity grounds, and since every site suitable for the erection of a windmill will be considered to be a beauty spot, we can expect many costly inquiries before wind-power production can be established.

Finally, can the author indicate the comparative capital and running costs of the Andreau type of machine compared with the conventional type?

Mr. A. J. Ramsay (*at Torquay*): Reference has been made to the damage caused to windmills during severe gales. The old windmill, used for corn grinding, irrigation, etc., was provided with slatted sails; the slats could be opened wide during gales to offer minimum wind resistance, and the sails moved to a non-operative position. Many modern sails are of the propeller type without slats. Could the author state what protective measures are taken to meet gale conditions?

I would also like some information about the method of obtaining speed and voltage control under varying wind pressures during normal operation as well as during gales. Has any satisfactory automatic method of speed control been devised? Alternatively, is the generator designed with a large range of field regulation, and is this sufficient to give automatic voltage control, within limits suitable for connection to the Grid system? No doubt the ideal would be a combination of both speed and generator field control.

It is possible that a supply of electricity for small outlying villages and hamlets might be obtained from windmills. In the south-western area, and particularly across Dartmoor, the question of amenities would be strongly argued, and I wonder whether the sight of a windmill would call forth the same storm of objection that arises whenever proposals are made for pylons and overhead mains-supply cables.

We may learn more yet from the Netherlands, whose people accept windmills as a matter of necessity and as one agent in utilizing a natural source of power.

Mr. W. J. Guscott (*at Torquay*): The problem of interference with amenities may appear to be a little frivolous, but I can assure the author that, in the south-west of England, where there are so many well-known beauty spots, including Dartmoor and Exmoor, the matter is taken very seriously indeed. Even important Government Establishments and the B.B.C. have been obliged to recognize this and take evading action to meet extremely strong local pressure designed to preserve the landscape.

The change in outlook and conditions in the last eight years or so, particularly since the electricity supply industry was

nationalized, puts a rather different complexion on the economic aspect of small wind-power plants, particularly those suggested for small isolated farmsteads. Whereas it was originally the established principle of supply authorities to require farmers to pay large capital contributions and/or annual minimum guarantees for extensions from public mains supplies and to base these charges on the capital expenditure involved, there now seems to be a tendency to attach as much or more importance to the strategic value of public electricity as an aid to food production, and as a measure to ensure a contented rural population. From the economic standpoint, rural electrification is now not often treated in isolation from other forms of load development, and payments required from farmers for extensions appear to be comparatively less than hitherto.

On the terms accepted by most Boards at present, a capital expenditure as high as £500 can be secured against a guaranteed revenue of £80–100 per annum. A 2 kW wind set would cost the farmer well over these amounts annually for a very limited supply.

The greatest possibilities in the development of wind generators appear to be in the production of small and medium sets for the export market.

Mr. L. C. Howard (*at Torquay*): I understand that a pumped storage scheme is contemplated at Blaenau Ffestiniog in North Wales. I would like to know whether the use of wind power for the pumping of water in parallel with the electrically driven pumps has been contemplated, and what the economics might be of such an addition to the scheme as planned?

Mr. L. H. Shelley (*at Torquay*): In certain areas there is no doubt that difficulties are being experienced from the amenity angle, thus preventing overhead mains-supply extensions, and it would seem that this type of generator might be an alternative if it could be accepted, having regard to the amenities.

The author mentions that, where these generators are established, they could easily be connected into the existing networks. I feel that this is not quite so simple as it sounds. In certain places the distance would not be any serious problem, but the ideal spots for location of the wind generator might be remote from any existing network.

The author does not indicate whether generation is at the national standard voltage. I imagine that generation at a high voltage might be considered economic, and I should be glad to have the author's views on this, and whether any tests have been made in this country and elsewhere on this particular aspect.

Mr. G. O. McLean (*at Bristol*): I notice that the author is having difficulties from objections in North Wales to the erection of the C.E.A. 100 kW unit, and wonder why he has not returned to one of his origina ideas of locating one of the two pilot units in Cornwall, where the annual 'run of wind' figure is very similar to that of North Wales. We who are responsible for the electricity supply in the Duchy would be very glad to give the author every assistance in choosing a site and in obtaining permission from the inhabitants for the erection of the unit.

We should also be very glad to give him assistance in instrument reading and maintenance work, absorbing the energy and, in fact, generally adopting the unit as our own.

May I also suggest that the china-clay slag heaps are of the ideal shape mentioned by the author, i.e. regular cones?

Mr. J. H. Toule (*at Bristol*): Has either of the experimental plants mentioned actually run in parallel with the public supply? It would seem that, during periods of no wind, the induction generator would be motoring from the supply.

What system of automatic control is employed to cut the wind generator in and out according to wind availability?

Mr. E. W. Golding (*in reply*): Mr. Venters rightly states that small wind-driven generators for isolated premises disappear as the main networks expand, but in many parts of the world without an electricity supply they have great scope. Battery storage is indeed expensive and should be limited to cover only really essential loads, using most of the windmill output as random power. His suggestion, put forward also by Mr. Griffin, for the use of resistors in the rotor circuit of the induction generator, to improve the governing, is sound, but his point about initiating shut-down in an hourly mean wind speed of 45–50 m.p.h. assumes that shut-down should occur when there are 60 m.p.h. gusts. Actually, machines would be designed to withstand such gusts as occur with an hourly mean wind speed of 60 m.p.h. It is good to have Mr. Venters's confirmation of the great potential value of wind power, combined with hydro-electric power, in Scotland.

Messrs. Griffin, Gatliff, Dixon and other speakers have raised the question of the best type of generator. For network operation there is little to choose between an induction generator and a synchronous machine, but in spite of the probable need for power-factor correction, and its higher cost, the former is more often favoured because of its greater stability in rapidly varying winds, its robustness and the ease with which it may be used in automatic operation. A synchronous machine may be preferable when an Andreau-type windmill, with its flexible pneumatic drive, is used. In order to supply an isolated community, a d.c. generator driven by a variable-speed windmill may be the best choice. The wind-driven machines being developed in Denmark have fixed-pitch blades which stall to reduce the power output at high wind speeds. This may be a cheaper method than that of changing the pitch of the blades.

Mr. Holttum's suggestion that two generators could be used to cover different wind speed ranges is feasible, but although the generator itself may amount to only a small percentage of the total cost, the design features needed might render the scheme uneconomic. The answer to Mr. Collins's question about future lines of development is that two lines should be followed simultaneously—one for machines connected to networks and the other for an autonomous machine to supply isolated communities. Mr. Knight rightly states that the capacity of a machine with a given rotor diameter will increase with rated wind speed, but the specific output will fall; there are few hours, annually, with very high wind speeds. Dr. Calvert's suggestion for a permanent-magnet alternator has already been considered. It may be feasible for small machines, especially for a single purpose such as water heating. To resolve Mr. Smith's doubts, the many components of the total cost of wind-power plants in the medium or large range of size are so nearly constant, whatever the capacity of the machine, that the cost per kilowatt should certainly fall as the capacity increases. Again, a large machine justifies a more remote—and windier—site, so that the annual output can be greatly increased.

Messrs. Ramsay, Guscott and McLean mention the question of amenities. It is certainly important that beauty spots shall not be disfigured, but many suitable sites do not come in this category. In Holland, Denmark and other countries windmills are accepted without objections. Mr. McLean's offer of assistance in Cornwall is welcomed.

Pumped storage, as suggested by Mr. Howard, would certainly be helpful provided that the necessary cost of construction were not charged to the wind-power plant. To cover Mr. Shelley's question, main networks are now sufficiently widespread to run close to many good wind-power sites. Mr. Toule can be assured that, during tests, both of the 100 kW pilot plants have run in parallel with the public network.

DISCUSSION ON

'THE STANDARDIZATION OF RETAIL ELECTRICITY TARIFFS'*

Before the MERSEY AND NORTH WALES CENTRE *at* LIVERPOOL *7th November*, 1955, *the* WESTERN CENTRE *at* BRISTOL *9th January, the* EAST MIDLAND CENTRE *at* NOTTINGHAM *10th January, and the* SOUTH-EAST SCOTLAND SUB-CENTRE *at* EDINBURGH *3rd April*, 1956.

Mr. E. J. Evans (*at Liverpool*): In Section 4.6 the authors state that there is little to choose between the alternative methods of measuring chargeable maximum demand, namely by measuring apparent power or active power, or, in simple terms, by basing the maximum-demand charge on metered kVA or, alternatively, on metered kilowatts and some method for evaluating power factor, e.g. metering kVAr. Perhaps the authors would explain why there is a divergence of opinion between Area Boards on this question. I understand that, of eight Boards with published maximum-demand tariffs, five use the kVA basis and three the kilowatt basis with some means of penalizing bad power factor. If there is little to choose between the alternatives, is there not a good case for some uniformity of practice over the whole country?

Mr. T. R. Smith (*at Liverpool*): In Section 3.3 the authors give some indication of the method adopted to obtain the number of assessable rooms for tariff purposes, and they indicate that these details were secured by a postcard survey. Table 1 shows that some quite excellent results could be anticipated from applying tariff 3. This alternative tariff shows a deviation of something less than 3% revenue disturbance over nearly the whole range.

I was associated with a similar postcard survey covering some 150000 consumers, and substantially all the postcards were returned, which enabled us to go forward and apply the tariffs. This was of considerable importance, but subsequently some doubt was cast on the accuracy of the replies, and when we made a house-to-house check, we found inaccuracies in 37% of the individual room returns, although the overall resultant accuracy was very satisfactory.

Later enquiries indicated that, because of the substantial numbers of semi-literate adults in the country, survey statisticians could not expect more than 60% completely accurate returns from this type of postcard survey. The fault lay principally in the inability to interpret the questions on the postcard rather than any deliberate falsifying of the returns. This position gave rise to considerably greater monetary disturbance than was anticipated.

Mr. W. Gilchrist (*at Liverpool*): The paper is, in effect, a résumé of the forms of standard tariffs already adopted by Boards throughout the country, which follow a pattern laid down by the National Retail Tariffs Committee.

While the broad basis has been followed by most Boards, within the framework of the forms of tariffs, there are considerable differences which it may be possible to reduce on fuller consideration of the effect of these tariffs.

The statistical methods of arriving at suitable forms and price structures set out in the paper were common to a number of Boards. In the result, however, more regard had to be taken of the financial effect on the various classes of consumers than on the true relationship between costs and prices.

I had hoped that the authors would have made reference to the relationship between fixed and running charges, particularly as between the domestic and industrial tariffs. A further factor which affects the charges is the price of coal, which varies between Boards.

I agree that the commercial group is the most difficult to which to apply standard tariffs equitably, and some further steps may be necessary to bring closer together the varying bases which are permissible under the national recommendations. In this Area, in order to overcome the difficulty of measurement of any kind, a fixed multi-block tariff was applied to all commercial and industrial consumers supplied single-phase having loads up to 15kW.

In the result, 60000 consumers out of a total of 76000 commercial and industrial consumers are operating on this tariff. This may also be the simplest solution for farm tariffs, provided that, in all cases of fixed block tariffs, the final rate is not set too low.

With regard to industrial maximum-demand tariffs, is an annual demand charge preferable to a monthly one, in relation to load-factor improvement?

Mr. W. H. Parkinson (*at Liverpool*): In Section 5.5 the authors mention the difficulty of the assessed demand for variable block tariffs for commercial users, the difficulty being to keep the assessed demand up to date. They then state in the same Section that 'the floor-area basis of assessment appears to be the more appropriate', followed by the proviso which very thoroughly confuses floor area and demand. Assuming that we remedy the difficulty of getting assessed demand up to date, would the authors agree that assessed demand more truly reflects the cost of supply?

In Fig. 8 there is a series of rates in which frequently the term 'and similar premises' occurs, e.g. 'hospitals, schools, public buildings and similar premises'. From the point of view of electricity supply, however, they are not very similar. I would like to say a word in defence of public houses. They appear with hotels, boarding houses, etc., and I think they deserve better, unless the opening times that the authors experience are different from those in this area. It seems certain that the public-house load presents a high load factor in relation to its contribution to the peak demand.

Mr. A. V. Milton (*at Liverpool*): The new tariffs in this area are generally reasonably equitable, but there are some anomalies which should be considered for future revision. Tariff 4, which is a variable 3-block tariff based on connected load, has caused monetary disturbance to a section of the consumers, and it needs closer analysis, as the average cost per kilowatt-hour for the small users is higher than with tariff 3, which is for still smaller users.

Farm tariffs have caused contention particularly with the commercial and industrial consumers, who fear, with some justification, that the supplies to farms are subsidized by other consumers. If the average costs of distribution to the farms were the same as those to commercial users—and I doubt very much whether this is so—that would not justify the results revealed in the 1954–55 accounts of this Area Board. For farms the average annual consumption per consumer is 4070kWh, and the cost per kilowatt-hour works out at 1·446d. For the commercial

* JOHNSON, A. O., and MARSH, N. F.: Paper No. 1798 U, March, 1955 (see 102 A, p. 533).

tariff the average annual consumption is 7315 kWh, i.e. 40% higher, but the cost per kilowatt-hour is 1·659d., i.e. 11·4% higher than on the farm tariff.

With commercial catering supplies, the authors appear to be a little naïve. In Section 5.6 they state that 'such loads as kitchens in schools, cafés and hotels, etc., fish-frying ranges, and the variety of bakers' ovens, *all* of which are of great value in helping to fill up valleys in Area Boards' load curves', and then give the examples shown in Fig. 10. These need to be related to Fig. 14; it will be seen that example (*a*) is a very good load, it makes a contribution to improving the load factor of the system and is entirely off peak; example (*c*) has its initial peak infringing on the high peak of the system, and the whole of the load is entirely during the day when the heaviest loads are in being; in example (*c*) the load peak is absolutely identical with the morning supply peak and also the load factor is not very good; in example (*d*) the morning load peak is again identical with the supply peak, and the evening load overlaps into the supply peak at the highest point round about 5 p.m.

Of these types of load the authors state that 'with such a competitive business, it is essential to have a simple tariff which is easily understood'. Why is it essential to have a simple tariff for these loads, which are similar to many industrial loads? The sole difference appears to be that, unlike lighting and motive power, the field of commercial cooking is held mainly by other fuels, but I suggest that tariffs should be based on cost analysis and not on cut-throat competition with other fuels.

Mr. H. Evans (*at Liverpool*): Whilst the tariff structure is acceptable in industry, although not in every case, people in this area do not appreciate the reasons for the first block being charged at a higher rate, and I wonder whether we have erred with the publicity. I am not excepting the Consultative Council, because they played some part in the early stages in considering tariffs after the Retail Tariffs Committee hurriedly produced their recommendations for a rooms basis, or floor area, and got away with them.

I think we ought to have made the public more appreciative of the desirability and necessity of having the higher rate for the first block. In this area we were merging 147 different tariffs, and it was not easy to explain to the public the reasons for that particular step, i.e. having one tariff with that first block at a high rate.

The domestic tariff has presented a large difficulty since it applies to the only unorganized section of consumers; all the others have some association through which it has at times been possible to give an explanation. The main difficulty came with sculleries, kitchens and unwired rooms, and I would like the authors to develop the reference to this, with particular reference to the discretion allowed to local assessment. My own experience in this area was the rigidity with which the principle of assessment for the domestic tariff was applied.

It is desirable, at present, to re-examine what has happened without involving ourselves in a further step of national tariffs, which some people seem to be talking about. I am in complete agreement with the possibility of a further step in the running charge, on the principle that those consumers using electric water heaters should have some benefit. It should be particularly recognized that, during the winter, the majority having a water-heating system of the back-boiler type use their electric water heaters off peak, and there should be some recognition of that fact in any further step in the domestic tariff.

The main difficulty in this area, with commercial and industrial consumers, is centred around the smaller industrial and commercial users. A further amendment has been applied in tariff 4 which is to receive the examination of the Consultative Council. Mr. Milton made reference also to the subsidizing of farm tariffs. If he is comparing them with the small commercial and industrial users, whose consumption is during 5 or 5½ days of the week and between the hours of 8 a.m. and 5.30 p.m., he must make some allowance for the farmers, who use electricity over a much longer period of the day and for seven days a week.

Mr. R. H. Cobbold (*at Bristol*): There appear to be three serious omissions from the paper. The first is that there is no attempt to justify standardization of tariffs or to define limits. It seems to be too readily accepted that a high degree of standardization is a statutory obligation. Appreciable variations are essential to meet different conditions in different parts of the country. This leads to the second omission, which is the failure to stress the importance of designing tariffs to be effective in load building.

The third omission is the apparent failure, when fixing new tariffs in 1948–49, to relate them to costs. The assumption that the new tariffs must produce the same revenue as the old tariffs is quite unjustified, although it may have been a convenient expedient.

Finally, I wonder whether the operation of the Retail Tariffs Committee does not unnecessarily delay the development of tariffs to meet new needs and changing conditions—the special needs of the holiday industries in the south-west is a case in point—and possibly stultify individual initiative.

Some evidence of the effective promotional features of tariffs in the south-west is provided by statistics of Area Board sales, which in the first half of 1955 were higher in this area than elsewhere in the country.

Mr. A. G. Milne (*at Bristol*): Those who criticize the prices of electricity are apt to overlook the fact that this Area Board suffers from the twin disadvantages of having the lowest population density, fewest consumers per mile of main and small industrial load, and of having to bear a disproportionate increase in the cost of electricity compared with Boards in cheap-coal areas.

The economy of the Board is marginal and unduly sensitive to the impact of the bulk supply tariff. The coal-price-adjustment component of that tariff depends on the price and quality of coal which the N.C.B. chooses to deliver to power stations, and, as a result, the associated Division has to accept unnecessarily expensive coal.

It would be comparatively simple to sell electricity if cheap tariffs could be offered. Nevertheless, it is the business of the Board to sell as much electricity as possible, and I was therefore surprised to note that the authors do not favour a two-rate or time-of-day tariff, because energy is supplied at a low price between certain hours to apparatus which has already registered a demand on the system at peak hours. This seems restrictive, as it would debar that class of consumer already taking a day load, who would be tempted and encouraged to seek further supply provided that it was available at a lower rate.

The high ratio of capital to revenue in the supply industry is rapidly swelling capital assets which are already substantial. Apart from the value of preserving large quantities of expensive and valuable equipment, there are also the aspects of security of supply and safety. Obsolescence does not play a big part in distribution equipment, and most of it should be required to function for its full depreciation life. This implies the allocation of sufficient revenue funds to preserve and maintain it. The difficulty of striking the right balance between under- and over-maintenance is well known, but in the interest of commercial solvency, the bias may be towards grudging expenditure on maintenance. Have the authors any knowledge of the way the pendulum swings, and would they consider it prudent to be on the safe side and frame tariffs to provide more money for preserving expensive and vital equipment?

Mr. S. Hartland (*at Bristol*): While it is essential to afford progressive advantage for domestic consumers with high load factors, we should not penalize the low-factor user because of capacity costs; it is our business to persuade the consumer to make more use of the supply. Too much has been said in the past of the effect on the system peak of the domestic load, and many exaggerated statements have been made. Normally, when a man leaves his home and goes to his place of work he diminishes his home demand and increases the industrial or commercial demand.

As an industry we ought to take our courage in both hands and eliminate entirely the two-part tariff and the need for an alternative flat rate. In addition, we ought to adopt universally the number of rooms as our assessment base and remove floor area from the domestic tariff. This would only be in keeping with what has already been done by the majority of Boards.

In Section 3.5.1 the authors use the word 'discretion' twice. This is important. The people dealing with the consumers must have discretionary powers over border-line cases with regard to assessable rooms. In other words, the border line should be blurred and not a definite cut which would remove discretion.

In Section 4.2 the authors suggest that the Board should have the option as to whether the maximum-demand charge should be on a monthly or annual basis. On this important point the option should be with the consumer and not with the Board.

Normally the fixed block tariffs are merely avoiding an issue; all block tariffs should have a variable basis as recommended by the Retail Tariffs Commission.

The demand charge on the industrial tariff should be on a kilovolt-ampere and not a kilowatt basis, and, undoubtedly, where the kilowatt basis has been retained this is merely because it is expedient in that particular geographical area. Finally, expediency should give way to proper tariff building.

Consideration should be given to thermal-storage heating on a restricted-hour basis to a price, if anything, less than the kilowatt-hour charge of the standard or industrial two-part tariff, because, surely, at the time this supply is being given it is coming from the most efficient generating plant and, in addition, the load is such that the I^2R losses are at a low level.

I advocate that contained within the kilowatt-hour price should be a sufficient increment to enable us to give consumers a full and cheap service in maintaining their apparatus in good working order. Fundamentally it is not electricity we sell, but a service to the housewife in reducing her labour and adding to cleanliness, health and leisure.

Mr. J. W. Dorrinton (*at Bristol*): I am pleased to be able to state that meter rents no longer exist in this area. To be quite accurate, under none of the published tariffs is any meter rent charged, but a rental is made for meters supplied under one of the special contract rates where the price per kilowatt-hour is so low that capital costs cannot be recovered.

Mr. T. G. Blayney (*at Nottingham*): With regard to charges for standby supplies, can the authors be more specific on the suggestion that some method should be considered of relating the charges to the period of breakdown, bearing in mind the risk faced by the Area Board of the breakdown occurring during the peak-load period?

In dealing with off-peak supplies, the authors are not in favour of a time-of-day tariff because it allows energy to be supplied at a low price between certain hours to apparatus which has already registered a demand at peak hours. Since the main aim is to sell more electricity during off-peak hours, I feel that a time-of-day form of tariff deserves further consideration, especially as it avoids the need for separate circuits in the consumer's installation, provided that the cost of suitable meters is not too high.

With reference to the forecast that fixed block tariffs will become more widely adopted, I feel that the low-income domestic consumer with small premises might well regard such a tariff as unfair, since it would not provide for low-priced electricity at a stage suited to his particular circumstances.

Mr. D. H. Parry (*at Nottingham*): Before April, 1948, the rateable value was a popular basis for calculating the fixed charge of a two-part tariff for domestic and some commercial users, but because the rateable value was determined locally, it was not an appropriate basis for uniform tariffs.

Now that the valuation for rates is a national responsibility should not a rateable-value tariff be reconsidered? This could be either two-part or block, but would the authors state whether the block tariff has proved satisfactory?

In 1952 the Ridley Committee, when reporting on the use of fuel, urged that electricity tariffs should closely correspond to costs of supply. This appears a reasonable requirement, and yet no discussion of costs appears in the paper.

Mr. G. A. Mills (*at Nottingham*): I am particularly interested in electricity costs to small and medium-sized shops. During the last three years some ten Area Boards have introduced standard commercial-premises tariffs, and from time to time criticisms and complaints have been made by consumers who find the new tariffs will increase their electricity costs, but there has been little comment from consumers who find the new tariffs will reduce their costs.

On a recent survey of small shops (the loading ranging from 2 to 10kW), it was found that the lighting installation represented about 90% of the total load, and in many cases the new standard tariffs had reduced the average price per kilowatt-hour as compared with previous tariffs.

It is interesting to note that the kilovolt-ampere and unit charges of new commercial-premises 2-part tariffs vary between Boards, and I wonder whether there is a possibility of the above rates being standardized at some future date.

Mr. C. R. Cooper (*at Edinburgh*): I agree with the authors in not favouring time-of-day tariffs for the encouragement of off-peak supplies. The idea of a time-of-day tariff is attractive, but the day-time rates which would be necessary in association with lower night-time rates would, of necessity, be higher than block tariffs now available for unrestricted use for the same purpose. This alone provides an almost insurmountable problem.

In this area it has been found that off-peak use can be encouraged in domestic premises as well as in commercial and industrial premises by suitable tariffs. Blocks of flats as well as individual houses have adopted off-peak space and water heating.

In Section 4.6 the last two paragraphs refer to the measurement of day-time maximum demand as distinct from night-time maximum demand in association with a monthly demand tariff. While I agree that a differential in the demand charge between day time and night time can easily be made with an annual-demand tariff, certain problems are introduced when a monthly-demand tariff is considered for the same purpose, and I feel that this matter should be treated with caution.

When the paper was written, there were two Area Boards in the South of Scotland. These have now been merged into one, and the nature of the organization has changed inasmuch as the new Board is also responsible for generation. A second standardization of retail tariffs has just been completed. One feature of the new tariffs is that there is no longer a separate commercial tariff. As the authors point out, the premises which are included in the omnibus term of 'commercial' are extremely varied. At the same time many of the commercial premises have load characteristics at least as good as many of the industrial premises, and, in fact, it is often difficult to decide whether premises should be classified as commercial or industrial. In

the South of Scotland District any consumer, other than domestic, farm or a public-lighting authority, has the option of adopting the general block tariff or the maximum-demand tariff.

With regard to the off-peak tariffs, these have been graded according to hours of use into three categories.

Mr. J. L. Egginton (*at Edinburgh*): There is a wide difference in practice between Area Boards in the method of assessing maximum demand in their industrial tariffs, and this matter is dealt with very briefly in the first paragraph of Section 4.6. Reference is made to the relative merits of apparent power and active power for the measurement of chargeable maximum demands. There is no reference in the latter case to a power-factor adjustment, and so presumably the intention is that the active power is used for measurement of maximum demand and does not include any inducement towards power-factor correction. I feel it is generally agreed that industrial tariffs must include some inducement to industrial users to improve their power factors if reasonable power factors are to be maintained on the system.

There are, in general, three methods of defining a maximum demand where power-factor improvement is encouraged. These are the half-hourly maximum demand measured in kilovolt-amperes, the square root of the sum of the squares of the non-simultaneous maximum demand of kilowatts and reactive kilovolt-amperes, and the maximum demand measured in kilowatts adjusted by the square root of the sum of the squares of the readings of the kilowatt-hour and kVA-hour meters.

The authors show, in Section 9.2.1, that the restricted-hour tariff is at present unattractive to a domestic consumer. Increase in the cost of energy or decrease in the cost of time switches might well reverse this conclusion, in which event there might be a very large number of time switches on the system. This, in turn, would introduce a problem when clocks are changed from Greenwich Mean Time to British Summer Time and vice versa, and I should be glad if the authors would state how they anticipate that these difficulties could be met.

I note that a feature of certain tariffs where kilowatt-hours were charged at a lower rate in summer than in winter has now disappeared, and perhaps the authors would explain why this is so.

Messrs. A. O. Johnson and **N. F. Marsh** (*in reply*): Messrs. Evans, Mills and Egginton have again raised the question of measuring chargeable maximum demand, and we stress that it is not so much a question of divergence of opinion between Area Boards as to whether kilowatt or kilovolt-ampere metering is adopted but largely a matter of practical considerations arising from pre-vesting practices.

Mr. Smith's comments on postcard surveys are noted; nevertheless, our own experience is that this form of survey has given satisfactory results.

In reply to Mr. Gilchrist, we consider that the annual-demand-charge basis is the most appropriate in cases where the consumer is able to exercise some control over his power requirements at various times during the year.

As Mr. Parkinson suggests, it may appear that public houses deserve better treatment than boarding houses or hotels by virtue of their official opening times, but the public rooms of public houses generally make little use of the supply other than for lighting purposes. This cannot be considered as a purely off-peak load, since very often a demand is created during the forenoon with extended opening hours on market days, and sometimes the evening load is building up before the cessation of use of supply in many day-time commercial premises.

Mr. Milton's comments on farm supplies being subsidized by other consumers are partly answered by Mr. Evans. When load characteristics are taken into account it will be found very misleading to compare farm supplies with commercial supplies on the basis of group overall average prices.

Mr. Milton also comments on commercial catering supplies, confirming the point made in the paper that commercial catering loads *taken as a whole* (and not individually) show considerable diversity between the different applications; it is this diversity which permits consideration of commercial catering tariffs at relatively low rates.

In reply to Mr. Cobbold, we do not agree that there was any failure when standardizing tariffs to relate them to costs. In most areas the former undertaking's tariffs had been increased since vesting day to bring them into line with costs, and in such cases standardization did not necessitate any further increase in annual revenue.

In reply to Mr. Milne, we agree that tariffs should be framed to secure sufficient revenue to meet the cost of adequate maintenance, and we are of the opinion that this is already the case.

We agree with Mr. Hartland that exaggerated statements have been made in the past regarding the effect of the domestic load on the system peak, but this may be due to a lack of appreciation of the vast change which has taken place in the characteristics of the domestic load during the last, say, 10 or 15 years.

With regard to the consumer's right to opt for either a monthly or an annual tariff, the majority of consumers are enjoying their option under the terms of monthly tariffs which were introduced at the request of the various trade associations on their behalf, but this right to opt cannot be indiscriminately permitted, especially in the cases of consumers who require supplementary, standby, and certain seasonal or intermittent supplies which can only be economically supplied on annual terms.

In reply to Mr. Parry, we feel that, had the reassessment of rateable value throughout the country been further advanced at the time when the work of the Retail Tariffs Committee started, this basis would have had to be seriously considered in place of those adopted. We are of the opinion, however, that no good purpose would be served by reconsidering the rateable-value basis at this stage.

Mr. Egginton asks why the feature of certain domestic tariffs, in which kilowatt hours were charged at a lower rate in summer than in winter, has disappeared. The main reason is that it is difficult to operate a tariff with different running charges in summer and winter under the now universally adopted system of continuous meter reading, as there are no longer any clearly defined 'summer' and 'winter' quarters.

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DISCUSSION ON

'THE ELECTRIFICATION OF THE MANCHESTER–SHEFFIELD–WATH LINES, EASTERN AND LONDON MIDLAND REGIONS, BRITISH RAILWAYS'*

Before the South Midland Centre *at* Birmingham *7th November*, the East Midland Centre *at* Derby *8th November, the* Western Centre *at* Bristol *14th November, the* Sheffield Sub-Centre *at* Sheffield *14th December*, 1955, *the* Northern Ireland Centre *at* Belfast *10th January, the* North Staffordshire Sub-Centre *at* Stafford *16th January, the* Western Utilization Group *at* Cardiff *27th February, the* Southern Centre *at* Brighton *29th February, and the* South-Western Sub-Centre *at* Exeter *8th March*, 1956.

Dr. E. H. Norgrove (*at Birmingham*): Just over 3 000 of a total of over 19 000 route-miles which British Railways operate to-day are electrified, i.e. about 16%; the revenue mileage is obviously a much higher percentage than this.

Section 2.2 mentions trouble arising from a speed limit of 65 m.p.h. which has to be enforced because of the track. In a recent report on railway accidents in 1954 it is stated that the extent to which heavy electric locomotives running at higher speeds cause more wear on the track than the steam locomotives they displace had not been fully realized when electrification had been planned, and three derailments occurred soon after the electrification. As a result of that the whole track is in the course of renewal, and there is now an embargo on the conveyance of short-wheel-based vehicles at the rear of the passenger trains travelling faster than 40 m.p.h. and a general speed limit of 60 m.p.h. between Sheffield and Penistone. The multiple-unit light-weight stock mentioned in the paper will help, but there will always be locomotive haulage of heavy freight, and thus much scope for improvement in the riding of electric locomotives, so as to reduce track wear.

On possible future extensions the authors mention that the choice of system is not really a subject for discussion, but any extension of an electrified system inevitably raises it. We have at least four systems in this country, namely 4-rail at 660 volts d.c., 3-rail at 650 volts d.c., overhead line at 1·5 kV d.c. and an experimental h.v. 50 c/s overhead system on the Lancaster–Morecambe–Heysham line. If this problem is not considered seriously now, we shall be in a situation similar to that which occurred with the old 7 ft ¼ in gauge. The same problem arises with the choice of braking systems, for locomotive use to-day often depends on the braking arrangement of the stock. There must clearly be a maximum through-running of stock, and multiple-unit trains make the problem more difficult.

Some Dutch and Swiss trains have heating vans, each containing a boiler and being equipped with a pantograph. If this method is adopted, any locomotive can be used for any train and passenger working need not be restricted to a particular few locomotives.

Electrical engineers ought not to lose sight of the very real threat to the future of electric traction offered by the Diesel engine. It seems rather dangerous to assume that electrification will extend automatically, and progress will be hampered if very active steps are not taken to render electrification more of an economic proposition than it is to-day, when it may fairly be said that we have lost the urban road-transport field almost entirely.

Mr. D. P. Sayers (*at Birmingham*): The authors will probably agree that nationalization of the supply industry has simplified their work in certain respects, because prior to the war there were three separate supply undertakers involved, namely the Manchester Corporation, the Sheffield Corporation and the Yorkshire Electric Power Co. The provisions of the Act governing the cost of supply to railways left a good deal to assessment, and I believe that the rates quoted by these three undertakings were very different. Sheffield quoted the lowest rates, and it may have been mainly for that reason that the railway company decided to install 33 kV cables from one end to the other. They would thus be able to use the cheapest power over a longer part of the route, while the other undertakings could not restrict the use of trains running within their area of supply. Would British Railways adopt the same method to-day, when the price of the supply is presumably much the same all along the line? Were the 33 kV cables installed because of the economics of the scheme, or are they required for operational purposes? The distance is only about 40 miles, and for three points of supply dealing with a maximum demand of 11 MW it would hardly seem necessary to use 33 kV cable.

I was interested to hear that the load factor has so far proved to be 55–60%. Supply engineers would be interested to know when the maximum demand occurs, and whether the railway load would improve or deteriorate the overall load factor of the supply system as a whole.

The total demand of this railway is given as 11 MW and the number of locomotives in use as 60; this gives an average of less than 200 kW per locomotive. Are the locomotives used only a few at a time, or is the average load very much lower than their available power rating?

When the scheme was being designed initially it was intended to use foreign small-oil-content circuit-breakers on the 33 kV side; what circuit-breakers have, in fact, been used here?

Dr. D. A. Bell (*at Birmingham*): It is interesting to note that the load factor is of the same high order as the 58% claimed for the French 50 c/s traction tests. The French claim that on one line the use of regeneration reduced power consumption by about 30%; has this any bearing on Mr. Sayers's comment that the average power consumption per locomotive is small?

Since the reduction of journey time between Glossop and Manchester is only 5 out of 35 mins, is the increase in passenger traffic due to the running of more trains, and if so is the ratio of passenger-miles to train-miles better than with steam trains?

Mr. H. M. Fricke (*at Birmingham*): What are the support spacings for the 33 kV cable?

I should like more details of the way in which the two bogies are coupled together in the $B_0 + B_0$ type of locomotive.

The early method of electrification on the centre section of the Southern Railway was by high-voltage a.c. overhead conductor, and the improved acceleration with third-rail d.c. trains has been very marked.

The track wear experienced with heavy electric locomotives on a 1 in 40 gradient suggests that abnormal track distortion could be produced.

Mr. R. Ledger (*at Birmingham*): The paper suggests that the locomotive-hauled passenger train will eventually be superseded by multiple-unit stock. Although such stock is ideal for medium-

* Broughall, J. A., and Cook, K. J.: Paper No. 1744, November, 1954 (see **102 A**, p. 159).

weight trains over moderate distances, and is the only possible type for suburban services, it is less suited for operating such trains as long-distance overnight expresses incorporating sleeping cars, holiday traffic (which can be handled by mixed-traffic locomotives released from freight duties for the purpose) and similar special services. I therefore suggest that there will always be some mixed-traffic locomotives, and that the difficulties of train heating will be solved by using electric heating as on the Continent.

Although the multiple-unit services form only a small part of the Manchester–Sheffield electrification, it is gratifying to see that the service to Glossop, 13 miles from Manchester, which runs at half-hourly intervals over a large portion of the day, can be maintained by what is, in effect, three trains, the eight units being formed into four 6-car trains, one of which is held in reserve for inspection and overhaul.

One small point concerning the motors for these trains should be mentioned. These machines, in common with much other equipment for this electrification, are of pre-war design, but when work was restarted after the war, it proved possible to redesign the field system in line with more recent practice, and as a result the motor weight was reduced from the figure of 6 123 lb quoted in the paper to 5 690 lb. Because of the amount of work which had already been done it was not considered desirable to redesign the armature.

Col. G. W. Parkin (*at Derby*): In view of the chequered history of this project, it is not surprising that a scheme which was estimated to cost £3 million in 1936 should on completion in 1954 have cost something in the region of £11 million. It is also to be expected that during the long interval between the placing of contracts and the completion of work, some improvements in design would have taken place. Nevertheless, it has been shown that working economies have been effected, not the least being a substantial reduction in coal consumption, and perhaps what is equally important, a substantial reduction has been effected in the train running times.

Most of us will have some knowledge of the modernization plan for British Railways, but one is impressed by the formidable problems likely to be encountered with the erection of overhead lines, irrespective of whether our future electrification schemes have d.c. or high-voltage a.c. contact wires. The authors refer to the fact that over 500 different designs of structure were necessary for a single-track mileage of 300, i.e. about 100 route-miles.

Could a breakdown of the cost of electrical equipment into, say, costs of locomotives, substations and fixed installations on the track be given?

Mr. J. D. Pierce (*at Derby*): I was rather interested to hear the authors state that they would have preferred to use indoor 33 kV switchgear. I should like to know the grounds for this statement, since the layouts shown would be admirably suited for the purpose.

I have heard that the drivers have experienced some trouble in communicating with each other when banking mineral trains, since the air hooters cannot be heard as clearly as the steam whistles. I believe that experiments are being carried out in other directions to overcome the difficulty, and I should be interested to know what is being done in this respect.

Mr. T. Baldwin (*at Derby*): Why do the authors prefer the tractive effort to be transmitted through the main underframe of the electric locomotive and the buffers to be mounted on the underframe rather than on the bogies?

Whilst appreciating that alternating current may offer other advantages in the future, in the past electrification has always been considered from the d.c. standpoint, so one would expect a scheme even such as this to be profitable. Do the authors feel that it has been, and that the capital expenditure on the Manchester–Sheffield–Wath electrification has been justified?

Mr. G. Y. Fraser (*at Derby*): One of the schemes to which many references have been made in the Press is that using industrial-frequency power at 25 kV. This would bring a substantial reduction in the costs of the fixed equipment by the use of simpler substations spaced 25–30 miles apart instead of 7–10 miles and also much lighter overhead equipment. One of the difficulties in adopting such high voltages in this country appears to be that of obtaining sufficient electrical clearance for the contact wire, owing to the smaller loading gauge here than abroad.

What clearances do the authors consider necessary for these high voltages in our damp smoke-laden atmosphere, in view of the very varied figures which have been suggested, and can such clearances be provided at reasonable cost?

Mr. W. E. Marrian (*at Derby*): It is stated in Section 4.3.3 that standby Diesel-driven generators have been installed at Gorton and Aldam to maintain supplies to signal circuits; have these ever been required to operate, and do they require much maintainance to keep them in working order?

I note reference to the close and friendly co-operation which has contributed to successful progress. Have any lessons been learned which will enable decisions, necessarily made at a high level, to be put into practice on site with little delay?

Mr. W. A. L. Creighton (*at Bristol*): Are the anticipated benefits of regenerative braking being realized? In this connection, was consideration given to the use of convertors, and, if the scheme had been prepared to-day, would they have been incorporated? Has any trouble been experienced with the regeneration resistors or the associated control equipment owing to regenerative surges?

The arrangement of pressurizing the high-voltage compartment reminds me of trouble experienced on one of our gas-turbine locomotives due to the ingress of dust and dirt into the control and switchgear compartments. Pressurization in this case was very successful. It would be interesting to know, however, whether any further filtration troubles have been experienced.

Although it has probably not yet been possible to obtain any firm figures for shopping periods, are the authors now in a position to give some views on this question based on experience so far obtained?

Mr. D. N. Clouting (*at Bristol*): In view of the increased wheel wear on the electric locomotive, has a similar increase been noted in railhead wear, or is this reduced since the surface would not be subject to hammer blows, as in the case of steam locomotives?

In the light of operating experience on this line, do the authors consider there is justification for the general adoption of Diesel-electric traction on the future electrification of all main lines in preference to electrification with supply taken from public mains by means of overhead wires?

Mr. D. L. Hore (*at Bristol*): Would the changes which would almost certainly have been made in the light of recent developments include the use of single-phase a.c. in place of 1·5 kV d.c.?

A figure of 96% was given as the availability of the electric locomotives: what is the corresponding figure for steam?

It appears that the difficulties in handling mineral trains on the gradients are made more onerous than necessary by the use of loose-coupled wagons. How long is this unsatisfactory method to continue?

Mr. R. J. Harding (*at Bristol*): In view of the difficulties with subsidence and the high costs which must have been involved, I am surprised to note that electrification of the marshalling yards was carried out instead of the generally accepted method of utilizing Diesel-driven shunters.

The description of train-heating boilers as a snag is rather harsh, our experience with oil-fired boilers on thermo-electric locomotives having led us to believe that their reliability is now of the same order as that of other auxiliary equipment, provided that adequate capacity is available to meet the heating requirements. In this respect I think that a 1000lb/h boiler is rather on the small side for trouble-free operation.

It is noted that tyre wear is heavy, and I shall be glad to know whether the tyres are of the special-quality high-tensile steel which have been found to give reasonable life under similar adverse conditions with steam locomotives. Finally, it would be of interest to know the comparable tyre-wear figures for the $B_0 + B_0$ and $C_0 + C_0$ locomotives.

Mr. F. G. Tyack (*at Sheffield*): Overhead-wire systems have advantages over third-rail systems, but require major engineering work, which cost £2610000 in the Sheffield scheme. Cost discourages electrification, notwithstanding its acknowledged benefits. 'Modernization and Re-equipment of British Railways', published in January, 1955, proposed electrification of parts of three main lines, and North-East London and Glasgow suburban lines, but not the extension of the Sheffield scheme or the completion from Reddish to Manchester Central. With the Sheffield electrification as a guide, the engineering work for these schemes may well prevent completion in our lifetimes, with extensions of the Sheffield electrification even more remote.

Third-rail systems are not completely bad, and for passenger trains are altogether preferable to steam. Without major engineering work, electrification is quick. There is extensive third-rail electrification in South-East England, and through-running to overhead wires will be necessary at system boundaries, west and north and across London (the 'Report of the London Plan Working Party' recommends abolition of termini and projection of railways across London). The British Transport Commission's Report for 1951 recommends increasing the third-rail voltage to 750 volts, with motors in series or parallel to suit either this or the 1·5kV system. The Sheffield locomotives have 700-volt motors. Could we have electrification quickly with third rails where suitable and overhead wires elsewhere? Without some such scheme we are unlikely to see electrification of the alternative Manchester–Sheffield route, with two tunnels, or of most railways in Britain.

Freight times have been remarkably improved by electrification. It is indeed remarkable for goods trains to ascend Wentworth Bank, 2 miles at 1 in 40, as if the track were level, and to descend under perfect control of regenerative braking with wagon brakes off. It is a pity that the speed limit of 65m.p.h. prevents startling improvements in main-line passenger train times, since public opinion might then urge electrification.

Apart from the line speed limit, the $B_0 + B_0$ locomotives are unsuitable for higher speeds. In 'Mechanical Design of Electric and Diesel-Electric Locomotives,'* Cox said that $B_0 + B_0$ articulated trucks had jerky movements, that speeds over 50m.p.h. were unsatisfactory, that such locomotives would be confined to freight trains and that passenger locomotives would be of the C–C type. But $B_0 + B_0$ locomotives *are* used for passenger traffic, although their riding is poor, and with the buffers and couplings on the bogies instead of the superstructure the jerky movements are transmitted to trains. Only seven C_0–C_0 locomotives were provided, instead of the 27 forecast by Cox. Why has this unsatisfactory change in policy been made?

The locomotives sometimes operate in twos and threes. Could control be simplified and the crews reduced by multiple-unit operation?

The Glossop trains have excellent performance and are a welcome contrast to locomotive-hauled passenger trains: they have better acceleration and higher speeds. Are the Glossop and Altrincham trains interchangeable? If so, why not operate the two lines as one?

The authors report slipping due to wet small-coal drippings. Could this be avoided by using 3-phase motors, linked by the frequency and fed by a motor-alternator on the locomotive?

The authors refer to difficulties of synchronizing controls on front and rear locomotives. Communication by pneuphonic horns between the front and rear drivers appears unsatisfactory, and signalling through the overhead wires is being tried, although carrier telephony seems the obvious solution. Have satisfactory results been achieved? Alternatively, could there be complete remote control by carrier telephony or radio?

Mr. W. J. Wright (*at Belfast*): In the event of failure of supply at any one of the three main substations, would the others be capable of supplying the area covered by supply failure and is it necessary to call the Board's engineers to deal with the emergency?

I note that 33kV h.s.l. cables are supported by hangers on concrete posts. Has trouble been encountered with this type of installation, particularly at joints, owing to vibration? Reference is made to the examination of joints by γ-rays for the detection of weakness of any sort. Has this method any practical advantage? It would seem more suited to the research laboratory and would probably be expensive.

Since all 11 substations with a total plant capacity of 47·5MW are operated in parallel on the d.c. side, what is the direct fault current obtained under certain fault conditions and how is the load shared?

Are the 150 and the 300c/s chokes associated with the neutrals of the rectifier transformers used for the suppression of voltage between no load and, say, 1% load. In view of the regulation of the rectifier this may be the case.

Are the d.c. circuit-breakers remotely operated or are they fitted with any reclose feature? Have troubles been experienced with the type of circuit-breaker employed?

Are the rectifiers arranged so that half the plant in each substation is capable of dealing with peak loads and connected so that in the event of failure of one set of rectifier equipment the other half feeds the system automatically? Since the installed capacity is 47·5MW and the highest recorded demand is 16·5MW, there appears to be a fairly safe margin for all conditions of service.

Mr. W. Szwander (*at Belfast*): In any railway electrification project the choice of the supply system is the first consideration. For the installation under discussion the decision was made before 1936, and therefore the choice of the 1·5kV d.c. system was the best possible decision for any new self-contained electrification project. As an illustration I can quote the example of the extensive electrification scheme (completed before the war) of the Warsaw suburban railways which was conceived as a starting phase of the intended subsequent main-line electrification in Poland. Exhaustive studies preceded the decision to adopt a 3kV d.c. overhead system. The higher voltage has, of course, both merits and demerits, but the main issue is the avoidance of a non-standard-frequency a.c. system. I have no doubts that further main-line electrification in Great Britain should be based on adoption of the standard-frequency a.c. system on the lines of the post-war developments in France. In this respect reference should be made also to the experiment with this system carried out during the modernization of the Lancaster–Morecambe–Heysham line. A recent development, which may prove of greatest importance for the future, is the experimental use of germanium rectifiers on an a.c. supplied locomotive. What special arrangements would be required on the future 50c/s locomotives with d.c. motors to enable them to

* *Proceedings I.E.E.*, Paper No. 967, March, 1950 (97, Part 1A, p. 196).

run on the 1·5 kV d.c. supplied lines between Manchester and Sheffield, such operation obviously being desirable in an integrated railway system?

Mr. J. Wainwright (*at Stafford*): I am particularly interested in the performance of the insulation of items such as overhead lines, traction motors and cables; can the authors make available the statistics which must have accumulated over the first four years of operation?

Sheffield, I believe, has the heaviest rate of deposition of air-borne particles in the country, and, in addition, steam trains are still used on the system. How frequently do the 33 and 1·5 kV insulators require attention, how does one determine when cleaning is necessary and how is the cleaning done?

The traction motors also are liable to be contaminated by polluted air. In the paper mention is made of the occurrence of this trouble in resistor cubicles, and it is therefore rather surprising that no information is given on its effects on the rotating equipment, which is surely far more vulnerable. Again, it would be useful if statistics could be given on the failures affecting the traction motors and details of the maintenance procedures (including routine testing) found necessary to keep the motors in service.

The paper implies that lightning disturbances may occur on the Wath section. Has any trouble of this nature occurred, and is this particular section of the line more liable to disturbances than the remainder of the system? Details of the impulse levels of the insulation of the overhead lines and the traction motors would be of interest.

Section 4.3.4 gives brief details of the filters intended to reduce rectifier harmonics. Apparently these units were installed in the first place to prevent telephone interference and the authors suggest that they are now no longer necessary. On the other hand, the results given by Warder *et al.** for a similar arrangement may make further investigation advisable, particularly if the cables pass through the Woodhead tunnel.

Mr. W. E. Richardson (*at Cardiff*): The foundations of the gantries shown in Fig. 6 seem to indicate that little attempt has been made to reduce the ground loading by spreading the foundations. This seems to be contrary to normal practice, and the authors' observations on this point would be welcomed.

Rectifying equipment is a notorious generator of harmonics. Troubles have been experienced in the past on the Southern Region 33 kV transmission due to this problem, and it would be interesting to hear whether any special precautions have been taken either in the cables or rectifiers themselves, so benefiting by experience gained in that Region.

Mr. L. H. Fuller (*at Brighton*): As an indication of the severity of the physical conditions on this project, the rainfall in Brighton averaged over 70 years is about 29 in, whereas at Woodhead it is 50 in; also, the maximum wind velocity over 1 hour is 70 m.p.h. with a recorded gust of 96 m.p.h.

I support the authors' suggestion for the future use of oil-filled 33 kV cable, but disagree with the use of 33 kV indoor switchgear. I endorse the use of 33 kV outdoor switchgear in this exposed region, since in the past I was associated with quite a lot of 33 and 66 kV outdoor switchgear in the vicinity of the Yorkshire side of the line.

Mr. G. G. L. Preece (*at Exeter*): The losses in the mercury-arc rectifier are merely that due to the arc drop and the transformer losses; on the higher direct voltages there is a distinct advantage, particularly on lower loads. The railway-traction load is spasmodic, and the overall efficiency is thus considerably higher than that of rotary machines. The rating of traction rectifiers is lower than with constant-load d.c. conversion, since the possible short-circuits and heavy overloads on traction are frequent; hence the high overload capacity. Glass-bulb rectifiers have been very successful for railway work because of their low rating, determined after many troubles experienced on ordinary urban traction work.

Mr. L. H. Shelley (*at Exeter*): I am interested in the authors' point of view regarding the adoption of the electropneumatic control of the contactors in the main circuit. On other systems in the London Midland Region the electromagnetic control was specified; I believe that all-electric control has some advantages, and a certain amount of space is saved. Will the authors comment on the results obtained from the rolling stock on the London Midland Region?

With the news that considerable electrification of railways is to take place in the near future, one assumes that the extensions will reach this part of the west country in due course. Has the erection of the overhead gantries supporting the conductor met with the approval of the local planning authorities throughout the route length? Particularly here, the planning authorities jealously guard the amenities, and I can imagine that the supporting structures shown would not meet with their immediate approval. This might cause the adoption of the third-rail system, although the paper suggests that the overhead equipment would be cheaper. Furthermore, is it desired that the incoming feeds for the systems, which presumably would be taken from the appropriate Electricity Boards, should be by underground cable from the main source? Here most of the rural areas are inevitably fed by overhead systems, and while these are generally reliable, there are times when supplies might fail. What degree of reliability is expected?

Mr. R. W. Adams also contributed to the discussion at Belfast.

Messrs. J. A. Broughall and K. J. Cook (*in reply*): The points raised in the discussions are set out below under the broad headings adopted for our replies to the earlier discussions.

Electrification Schemes.—Publication of the British Transport Commission's modernization plan and of its decision as to choice of system may perhaps afford the answer to Dr. Norgrove's fears that electrification may not be an economical proposition, to Mr. Baldwin's question whether the electrification of the Manchester–Sheffield–Wath line is really profitable, to Mr. Tyack's proposition regarding the respective fields of use of third-rail and overhead systems and to Mr. Adams's point.

In answer to Col. Parkin, the approximate breakdown of estimated capital costs is as follows:

		%
Rolling stock:		
Locomotives	£1 240 000	18
Multiple-units ..	£88 000	2
Substations and cables ..	£1 565 000	23
Overhead equipment ..	£3 800 000	56
Other costs	£61 000	1
	£6 754 000	100

Power Supply.—In answer to Mr. Sayers, the provision of three supply points for this Y-shaped line would probably be the correct arrangement, even with equal prices at all supply points.

As Dr. Bell supposes, the use of regeneration is partly responsible for the relatively low net consumption per locomotive; the actual economy is difficult to evaluate in this case, but probably amounts to 15%.

In reply to Mr. Wright, supply can be maintained to all sections if one supply point is lost and the necessary interconnections can be made after telephonic consultation with the Board's engineers; this aspect tends to justify the choice of 33 kV for the cables, which was questioned by Mr. Sayers.

* WARDER, S. B., FRIEDLANDER, E., and ARMAN, A. N.: 'The Influence of Rectified Harmonics in a Railway System on the Dielectric Stability of 33 kV Cables', *Proceedings I.E.E.*, Paper No. 1025 S, August, 1950 (98, Part II, p. 399).

Transmission System Cables.—In reply to Messrs. Fricke and Wright, the cable supports are 6 ft. 6 in apart, and no trouble has so far arisen from vibration at joints or elsewhere. The γ-ray technique has proved to be a simple practical device as well suited to the field as to the laboratory.

Substations and Track-Sectioning Cabins.—In reply to Mr. Sayers, the 33 kV circuit-breakers are of the bulk-oil type. In reply to Mr. Pierce, the preference for indoor switchgear is mainly on account of greater convenience of inspection and maintenance, and we note that Mr. Fuller does not share this view. The relative merits of indoor and outdoor switchgear have long been the subject of argument, and both types will undoubtedly continue to be used.

In answer to Mr. Marrian, the standby sets at Gorton and Aldam have been operated on isolated occasions when there has been interruption of supplies from the Yorkshire Electricity Board. Maintenance has been practically nil, but they are run for short periods regularly to keep them in condition.

In answer to Mr. Wright, the interconnection of the substations via the overhead line automatically ensures a reasonable distribution of load between the substations because of the self-regulating characteristic of the rectifiers and line. The maximum d.c. fault current on one substation may momentarily rise to a peak of 20 kA. No troubles have been experienced with the circuit-breakers, which on this line are not equipped with a reclose feature. His understanding about load sharing of rectifiers and the suppression of voltage rise is correct.

Overhead-Line Equipment.—In answer to Mr. Wainwright, the renewal of the overhead-line equipment has been nil, other than where accidental damage has occurred. Wearing strips have been fitted at a small number of locations where wear has occurred on account of hard spots or sharp changes of elevation.

The frequency of attention to 33 and 1·5 kV insulators varies between 2 and 6 months according to atmospheric conditions, and cleaning is by detergent solution. To determine when cleaning is necessary and how cleaning is done, observation is kept by patrols and timetables are worked out by experience.

Lightning trouble has occurred on two occasions—one being a particularly severe storm on the Pennines. After a considerable interval, and subsequent to these discussions on the paper, two further lightning strikes have damaged locomotives.

In reply to Mr. Richardson, the specific ground loading is not heavy and the main factor in design of foundations is to withstand overturning moments.

Rolling Stock.—In answer to Dr. Norgrove, overall speed restriction is due to characteristics of line. There is considerable scope on all bogie-type electric locomotives to minimize effect on track.

In answer to Mr. Clouting, greater unsprung weight tends to equal the effect of hammer blows on steam locomotives.

In answer to Mr. Fricke, track distortion is not abnormal on this section, where running is relatively slow and the curves are not sharp.

In answer to Dr. Norgrove, the heating-van solution has much to commend it, but is always more attractive to the engineer than to the operating department of the railway.

In reply to Mr. Sayers, although the maximum demand has aggregated 14 MW since the paper was written, it is not accurate to divide this by the total number of locomotives to determine the average load, because traffic does not permit of all being used for 24 hours a day. The average load on typical service runs is nearer to 600 kW. The maximum demand generally occurs outside the hours of the normal industrial peak. Because so much of the coal traffic is handled at night, the load factor certainly surpasses the national load factor: the monthly value varies between 50 and 68%.

In reply to Mr. Baldwin, there is a fundamental difference of design representing two trends. Tractive effort is transmitted through the underframe on the C_0–C_0 locomotives and buffers are mounted on underframes, while on the $B_0 + B_0$ locomotives the buffers are mounted on bogies and the tractive effort is also transmitted through the bogies.

In reply to Mr. Pierce, as driving technique improves, the need for communication dwindles, and development on the aspects raised by Mr. Tyack is not yet complete.

Mr. Creighton will appreciate from our reply to earlier questions that we do consider regeneration has given the benefits expected on this line; the equipment has been almost trouble free. We do not consider that convertors would be justified by the further economy that would result from their use.

In reply to Messrs. Creighton and Wainwright, the filters can now be kept satisfactorily clear, and the effect of dirt on rotating equipment has not been serious.

In reply to Mr. Creighton, general repair-shop periods have not yet been reached. In reply to Mr. Hore, availability of steam locomotives is 84%. The difficulty is that many wagons are not fitted with continuous brakes. Mineral wagons will be fitted with continuous and automatic brakes under the railway-modernization programme.

In answer to Mr. Harding, tyres are of D-quality 56–62 tons ultimate tensile strength, and the tyre-wear figures of $B_0 + B_0$ and C_0–C_0 locomotives are similar.

In reply to Mr. Tyack, we question the rightness of comparing any C–C locomotive with any B–B locomotive as regards riding qualities and high-speed performance. Some advantage would accrue from arranging for multiple-unit working, but on this section of line the reduction of crews would only be small, but it is desirable to have a locomotive at the rear on the 1 in 40 gradient. Two or three locomotives coupled together are always returning light, owing to unbalance of traffic. Slipping could be avoided as proposed by Mr. Tyack, but there are other simpler methods.

In reply to Mr. Szwander, and to a point raised by Mr. Adams, it is intended eventually to convert 1·5 kV d.c. systems to alternating current to avoid undue complication in providing dually equipped locomotives.

DISCUSSION ON

'SUPERVISORY EQUIPMENT FOR THE INDICATION OF SHAFT DISTORTION IN STEAM TURBINES'*

AND

'THE ELECTRICAL MEASUREMENT OF STEAM-TURBINE ROTOR MOVEMENTS, WITH SPECIAL REFERENCE TO THE OPERATION AND DESIGN OF MODERN POWER PLANT'†

Before the NORTH-EASTERN CENTRE‡ *at* NEWCASTLE UPON TYNE 12*th December*, 1955, *the* SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP *at* BIRMINGHAM 9*th January*, *and the* EAST MIDLAND CENTRE‡ *at* NOTTINGHAM 21*st February*, 1956.

Mr. F. Dollin (*at Newcastle upon Tyne*): Turbine designers and operators have always wanted to know more about the internal behaviour of their machines. Some 25 years ago an optical method was developed which enabled the clearance between the stationary and rotating blades inside the turbine to be observed. It involved fitting a quartz window in the wall of the casing and the use of a system of illumination and a short-focus telescope. The instrument proved very successful as applied to a small experimental turbine, and was used during investigations on one central power-station turbine. It is, of course, essentially a laboratory instrument and not suitable for commercial application.

Another method that we have used for measuring variations in clearances between stationary and moving parts comprises a nozzle pipe containing two orifices in series, which is inserted through an aperture in the casing and set with its end face reasonably close to the surface of the body whose relative movement is to be observed. The inlet end of the nozzle pipe is connected to a source of fluid supply at constant pressure, and the pressure measured in the space between the two nozzles is a function of the gap at the discharge end of the nozzle pipe that can be determined by calibration. Instruments of this type are more readily applied to measurements on power-station turbines than the optical instrument, but their use is for special investigations and not as permanent supervisory equipment.

For permanent supervisory equipment there is no doubt that instruments of the electromagnetic type, basically similar to those described in the paper, are the most convenient and versatile, and I agree that the eccentricity indicator is the most important item. Experience shows that a shaft can develop quite a large eccentricity when running at speed, with no evidence in the magnitude of bearing vibration. One cause which may give rise to such conditions is a touch at the glands, and should this occur during starting, the usual procedure would be to reduce speed or retard the rate of acceleration. Should a high-eccentricity reading develop when the machine is running on load, however, it becomes a problem for the operator to decide whether it is a warning of a dangerous condition developing or whether the machine can be left running on load. There have been instances of considerable eccentricity developing for a period and then dying away without the machine apparently taking any harm.

On all the records which I have examined, differential expansion has been comparatively small and does not seem to be an important limiting factor in the rate of starting and loading our machines.

In the quick-start schedules now specified by the C.E.A., for even the largest turbines with steam temperatures above 1 000° F, the temperature difference between the steam and the metal after an overnight shut-down is a very important factor. In order to obtain a tolerably accurate measurement of the temperature of the steam before admitting it to the turbine, it is necessary, on a unit boiler-turbine installation, to blow a considerable quantity of steam to drain and to have thermocouples on the drain connections as well as in the steam chests and turbine casing wall. These temperatures can most conveniently be recorded by an intermittent-type multi-point recorder.

Supervisory equipment is at present being employed on a 15 MW gas-turbine in the Dunston A power station. The critical measurements are clearances in the radial direction between the shaft and the casing, and as the shaft material is austenitic it is necessary to employ capacitance-type pick-ups instead of the electromagnetic type. The extremely high ambient temperature is a source of difficulty on this machine, as indeed it is sometimes found to be on high-temperature steam turbines.

Mr. G. H. Hickling (*at Newcastle upon Tyne*): There is a remarkable similarity between the types of equipment for turbovisory measurements developed by the authors and by the organization with which I am connected‡ and in the experience gained with them. We have, for instance (though only rarely), recorded shaft behaviour very similar to that shown in Fig. 5 owing to a light gland rub—resulting in no actual damage. Trends in the design of eccentricity-measuring equipment have been almost identical, although for other measurements our own equipment differs slightly in being supplied, for simplicity, direct from the 50 c/s mains. As regards presentation, separate 'unit' measuring circuits have been developed in which the complete equipment, apart from the detector, is housed in the case of a combined recorder-indicator instrument, mounted on the normal turbo-generator gauge board.

With regard to the placing of the relative expansion detectors in Fig. 1, their distance from the cylinder end may be regarded as excessive, giving rise to possible errors in estimating the true blade clearances at the outlet end of the turbine.

Although conventional turbovisory eccentricity-measuring equipment has been fitted as a temporary expedient to one gas turbine of our manufacture, in which the shaft was of ferritic material, the tests on the Dunston A machine, to which Mr. Dollin has referred, were essentially of the nature of a special investigation made during the initial testing period only. Portable capacitive-type displacement-measuring equipment was used, with detectors (in air) adjacent to the shaft, between the

* ANTRICH, D., GARDINER, H. W. B., and HILTON, R. K.: Paper No. 1622 S April, 1954 (see 102 A, p. 121).
† ASHWORTH, J. L., HALL, J. S., and GRAY, A. H.: Paper No. 1680 S, September, 1954 (see 102 A, p. 131).
‡ This refers to the paper by Messrs. Ashworth, Hall and Gray only.

‡ KELLY, E. D.: *Heaton Works Journal*, December, 1955.

cylinder and the h.p. end bearings of h.p., i.p. and l.p. turbines. The initial measurements indicated appreciable deflection of the gland housings due to cylinder distortion, and enabled corrective measures to be taken before serious damage occurred.

The main problem of interpretation posed in the paper is probably that of the development of transient bends in steam-turbine spindles, during rapid temperature changes, where not attributable to a rub. It is tentatively suggested that there may be a useful analogy between this phenomenon and that of thermal unbalance recently encountered in electrical rotors—although, in this instance, due to inequalities of heat transfer rather than of cooling. It is possible that variable 'pinch fit' effects may contribute to such differences in heat conduction.

Mr. E. V. Hardaker (*at Birmingham*): The eccentricity, as measured at that point on the shaft where the measuring equipment is located, may be less than that at other points along the shaft. What is the relation between the measured quantity and the maximum which may occur, and what allowance, if any, is made to compensate for such a possible difference?

Mr. T. Howard (*at Birmingham*): With reference to the paper by Messrs. Antrich, Gardiner and Hilton, can the authors state what effect distortion or movement of the bearing pedestal which houses the magnets can have on the eccentricity reading?

What would be the maximum eccentricity reading at which they would be prepared to put the turbine on load? I am thinking of an equipment which gave peak-to-peak figures, and where the set had been running at full speed for 1½ hours and was still showing 0·007 in. None of the charts illustrating these papers show eccentricity readings greater than 0·0045 in, although one speaker mentioned 0·005 in. Are these the actual eccentricities or double the figures?

Mr. P. M. Martin (*at Birmingham*): I was rather intrigued by the remark of Messrs. Antrich, Gardiner and Hilton that the casing had come up against an obstruction which prevented expansion. I find it rather difficult to visualize the obstruction, and would be interested to know what they had in mind.

Mr. R. Cotterill (*at Birmingham*): What is the relationship between vibration and eccentricity? Has it any connection with where the eccentricity is coming from?

Mr. H. M. Fricke (*at Birmingham*): I would like more information on the clearance between the coils and the disc. The actual differential is so very small that it seems necessary to keep the clearance down to a minimum.

Mr. J. E. Hewitt (*at Birmingham*): I can understand vibration with the onset of eccentricity, but what is the explanation for an increase in vibration when the eccentricity is negligible or falling off? The equipment with which I am associated has turbovisory equipment on the h.p. and i.p. cylinders, and we do get the condition where rises in vibration of both i.p. and h.p. pedestals coincide with a falling-off of eccentricity.

On the run-up of turbines, the eccentricity is often of a low order, but vibration is relatively high. Should the run-up be delayed for this?

Mr. E. R. Knight (*at Nottingham*): The equipment described by the authors is proving invaluable in developing operating techniques which give maximum rates of running-up and loading consistent with safety in operation. This is particularly the case in the commissioning of prototype machines.

Whilst a quick run-up is desirable in the interest of economy and for other reasons, rapid loading is of greater importance in view of the high rates of system loading now experienced and the increasing proportion of large units operating at high pressures and temperatures now coming into service.

The use of turbovisory equipment inevitably focuses attention on a number of shortcomings in the machines themselves, which in the past have limited starting and loading rates and have also led to early deterioration in machine performance. Amongst these I would mention h.p. gland construction (a fruitful source of shaft bending), freedom for expansion both of casings and couplings, and casing temperature control. All these factors are now receiving attention, and the information given by turbovisory equipment has considerably accelerated the development of suitable designs and improved operating techniques. A further desirable feature in turbine construction deserving more attention is the provision of simple access for balancing purposes.

As with many new devices, the interpretation of results recorded needs careful study, and the paper is most helpful in this respect.

With regard to the turbovisory equipment, I feel that over-elaboration is to be avoided, and I think that present systems might, with advantage, be simplified, particularly by the use of multi-point recorders and improved means of correlating the various records. An essential feature of all indications must be a rapid and certain means of checking their accuracy against basic standards. Despite its difficulty, I feel that a means of measuring shaft eccentricity at its mid-point and shaft, rather than pedestal vibration, would also be advantageous.

I should like to have the authors' views on the desirability, or otherwise, of cooling the turbine during off-loading of unit plants, operating on a two-shift basis, by reducing steam pressure and temperature, with a view to improving starting conditions following an overnight shut-down.

Mr. E. Houghton (*at Nottingham*): When interpreting the records from this equipment, great faith has to be placed in the accuracy and long-term stability of the measuring instruments. The inductance of the detector magnets will not vary directly as the displacement of the iron, except over a very limited range. The output fed to the recorder will depend on the voltage and frequency of the supply and on the valve constants.

Bearing in mind the changes in ambient temperature of the bearing housing and vibration, was it necessary to consider any special mounting for the detector magnets? Has consideration been given to the application of negative feedback to several stages as distinct from the single cathode-follower stage? Alternatively, has it been useful, in developing the equipment, to have another line recorded on the chart from another pair of detector magnets, in adjacent position, feeding through the same components but reading a fixed reference? This might be done by adding a time switch to the existing equipment.

Mr. O. S. Woods (*at Nottingham*): I note that the authors refer to the inconsistency between vibration and eccentricity readings. Have American designers found the answer to this, since it is now the practice in the United States to use vibrometers, which pick up shaft movement and not pedestal movement, and to rely on such instruments for the safe operation of large turbo-generators?

Mr. H. H. Ledger (*at Nottingham*): The long-term value of permanent records in the study of turbine behaviour is, of course, obvious. The interpretation of chart irregularities in terms of immediate action to be taken by the attendant would, however, appear to be a matter requiring considerable experience and intelligence, particularly in view of the amount of information presented. Some time must also elapse before the effect of any irregularities detected by the equipment can be completed on the chart. Also, during this period the attendant's attention may be occupied elsewhere.

When a dangerous condition is detected it would therefore appear logical for a degree of automatic correction or at least an alarm signal to be introduced. I should like to know whether any developments along these lines are being considered.

Mr. G. B. R. Feilden (*at Nottingham*): During the development of the Whittle jet-propulsion gas-turbine, I had experience of a variety of turbovisory equipment. It had been the practice to

record the exhaust temperature on a sensitive pen recorder, and in one endurance test the otherwise straight record showed a sudden step upwards of about 5°C. This change was not noticed immediately, though frequent checks were made on the running vibration of the engine. At the conclusion of the test, an inspection showed that half of one of the 80 turbine rotor blades had disappeared down the jet pipe. Had turbovisory equipment of the type described by the authors been available, a more precise indication of the nature of the defect would undoubtedly have been obtained.

Turbovisory equipment is likely to become of great importance in the second stage of the nuclear power programme. In power plants of the Calder Hall type, the turbine section is of conventional design, but in more advanced types of nuclear power plant, it is probable that closed-cycle gas-turbines will be used, and that some radioactivity may be present in the turbine. This will make it impossible for the operating personnel to approach the plant, and will render the remote indication of the running even more essential than it is at present.

I would defend the gas-turbine as a prime mover for quick starting to meet peak load demands. The two 15 MW sets at present used by the C.E.A. were both designed ten years ago, and, being prototypes, they were built largely in accordance with concepts applicable to steam turbines. In adopting this course, the designers followed the only possible line, as any failure due to the adoption of untried ideas would have been very costly. The designers of two British gas-turbines having outputs of about 1 MW had been able to adopt a different policy, owing to the fact that in each case it had been possible to build a prototype to try out the many novel features which were incorporated in these designs. As a result, machines had been produced which were capable of very rapid starting and acceptance of load, and in the case of one manufacturer, a single machine had been started over 1 600 times and accepted full load within two minutes on each occasion. Whilst I realize that units very much larger than 1 MW are required by the C.E.A., the fact remains that the way is now open for the design of larger gas-turbines which incorporate the constructional principles that have been adequately vindicated in the performance of the smaller British machines.

Mr. R. C. Gething (*at Nottingham*): While disclaiming any knowledge of steam-raising plant, I notice that, in a restart after a short shut-down, steam was admitted to the turbine at a lower temperature than that of the casing of the turbine, thus causing cooling and accelerated contraction and not an immediate change to expansion and warming up to working temperature. I wonder why steam from other boilers in the station could not be used, or alternatively why steam could not be raised on the unit's own boilers, so that the initial admission of steam to the turbine could be at the same or slightly greater temperature than that existing in the turbine casing.

Mr. H. J. Gibson also contributed to the discussion at Birmingham.

Messrs. D. Antrich, H. W. B. Gardiner, and **R. K. Hilton** (*in reply*): We agree with Mr. Hardaker that the eccentricity measured at the one readily accessible point on the shaft may be less than at other points along the shaft. Owing to the complex way in which the shaft deflects along its axis it is not possible to relate the measured eccentricity with that which may occur at any other position. However, after some experience on a particular set, it is not difficult to relate the measured eccentricity to the general performance of the set.

In reply to Mr. Howard, gradual movement of the bearing pedestal, to which the detecting coils are rigidly attached, does not affect the eccentricity reading but would merely cause a change in indication on the horizontal and vertical displacement meters. With regard to the maximum allowable eccentricity at which one would be prepared to put the turbine on load, this depends on the characteristics of the particular set considered. In general, where a radius of eccentricity of the order of 0·005 in has been observed, the set has been allowed a further warming-up period. Our equipment indicates and records the radius of shaft eccentricity.

We have no precise details of the nature of the obstruction to which Mr. Martin refers, but we understand that, during the course of the casing expansion, a steam pipe fouled a temporary obstruction on the foundation.

Both Mr. Cotterill and Mr. Hewitt raise an interesting point concerning the relationship between vibration and eccentricity. The design of the bearing pedestal is such that a greater flexure is to be expected in the horizontal rather than in the vertical plane, and if any vibration is present, the detector coils which we have described will measure the combined effect of vibration and eccentricity; they will not resolve the resulting complex signal into its two components. Provision could be made to separate these components by using more elaborate equipment, but we feel that the provision of vertical as well as horizontal detector coils will give some indication of this effect. Further operational experience, however, will be necessary before the relationship can be clearly established.

In reply to Mr. Fricke, the clearance for the radial detector coils is of the order 0·150 in and that of the axial coils 0·600 in. We have found that this gives adequate sensitivity together with linearity of response.

Messrs. J. L. Ashworth, J. S. Hall and **A. H. Gray** (*in reply*): Mr. Dollin has supplied interesting, and familiar, details of the history of the development of electrical turbovisory gear. Experiences related by Mr. Dollin and other speakers of the inconsistency between indicated eccentricity and that of vibration show that the phenomenon appears to be general with steam turbines. This would seem to compel the conclusion that in instances where, for example, a large eccentricity reading is showing, without commensurate accompanying vibration, we are dealing with movements of journal centres with respect to the bearings, not necessarily associated with bends; or with significant displacement from the axis of rotation, of the centre of mass of the shaft.

In this connection, a rub at the glands would be expected to produce a bend, and if, under even these circumstances, less than the expected vibration occurred, it would seem necessary to include in our conception of the movement of journals in bearings, an automatic correction for the bend by an equivalent mass displacement in the opposite direction. It is worth remarking, as already stated in the paper, that, in our experience, turbovisory gear has never failed to give warning when real trouble was impending, possibly due, to some extent, it may be conceded, to intelligent interpretation of the instrument against the background of a particular machine.

There is no doubt that the reduction of temperature differential between incoming steam and metal is an important factor in smooth quick starting. We would agree with Mr. Hickling that the problem of thermal bending of steam-turbine rotors is not yet fully understood. It would seem good practice to avoid any construction which could contribute to variable heat transfer rates.

Mr. Hardaker suggests it is very difficult indeed to establish a definite relationship between the reading of the eccentricity meters and the actual displacement of the mass of the centre of the shaft. However, we would stress the fact that this instrument must be regarded as a comparator, rather than a means of obtaining a precise positional measurement.

In reply to Mr. Cotterill, so far as we are aware at present, no

known relationship is available between the measurement of vibration and eccentricity.

Mr. Gibson asks what is the real purpose of the equipment. We would state that it has proved of real value during the commissioning of a set, and is, at the same time, by virtue of the records available, a means of obtaining smooth and efficient performance during its normal operational life. It is also true that much information is being produced by the equipment which should prove of real value to design engineers.

With reference to Mr. Fricke's query, we would advise that the air-gap used in conjunction with each eccentricity detector is 0·063 in, whilst that associated with each differential expansion magnet is 0·5 in.

We are very interested in Mr. Hewitt's observations, and whilst their experience indicates that eccentricity is noticeable before vibration, inconsistency between eccentricity readings and the level of vibration would lead to the conclusion that it is possible to have a very high level of vibration with a low indicated eccentricity. That this has not occurred within our experience, would seem, in view of Mr. Hewitt's experience, to be due to some design feature whose bearing on the problem has not yet been fully appreciated.

If we experienced high vibration with a low reading of eccentricity we would certainly proceed with due caution.

We agree with Mr. Knight when he considers that the measurement of shaft eccentricity at its mid point would be preferable to the present measurement point outside the bearings. Unfortunately, so far, practical difficulties have prevented internal measurement. We would be reluctant to agree that there is anything fundamental in turbine operation to make it advantageous to cool a machine during the shutting-down period in order to facilitate safer starting. The arguments in favour appear to be associated with the difference in behaviour of a contracting machine compared with an expanding machine, and where, in fact, there is some difference in favour of the expanding machine, this would appear due to particular design features. Where a design is suitable, it would appear that the higher standing temperature of the machine which has not been cooled should be conducive to quicker starting.

Mr. Houghton raises the question of long-term instrument stability. We appreciate the difficulties of obtaining this performance and have considered it desirable to keep the apparatus as simple as possible, but to maintain the overall accuracy by providing a simple test unit in the apparatus itself, whereby an initiating signal can be injected into the system for checking purposes at periodic instances.

Mr. Woods raises an interesting point. It should be noted that most British experience with eccentricity gear refers to two-bearing rotors flexibly coupled to each other, whereas American experience refers to solidly-coupled shafts giving, in effect, multi-bearing rotors. With this latter type of rotor it would seem that there should be less tendency for journals to move in the bearings, and turbovisory instruments should give reliable indication of shaft bending. The vibration indicator gives an indication of the out of balance, and it would appear, therefore, that there is a use on these machines for both types of instruments.

Mr. Ledger suggests the fitting of automatic control gear or some suitable alarm device. We agree that sufficient experience of turbovisory gear is now being accumulated so rapidly that it is possible that suitable alarms and possibly automatic control can be introduced in the not too distant future.

Mr. Fielden, in an interesting contribution, stresses the necessity for remote indication in connection with the new power stations. We entirely agree with this, and believe that turbovisory equipment will provide an increasing contribution to the safe and efficient operation of the future super power stations.

With regard to Mr. Gething's query concerning steam temperature we would advise that it is already controlled to provide satisfactory starting.

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ABBREVIATIONS

(P)—Address, lecture or paper.
(p)—Subject dealt with in a paper or address.
(D)—Discussion on a paper.
(A)—Abstract of a paper or address.

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